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As beaver return to North Carolina, their role as ecosystem engineer is becoming more apparent. In this study, I examine variables related to beaver dam construction and ponding to look for relationships that may provide insight into the long term impacts of beaver in modifying stream channel forms. Dam construction and other physical features created by continued beaver activity are studied to provide a matrix of variables, which are analyzed to determine correlations between these features. Log-linear regression indicates that several variables do have significant relationships, and form a web of relationships that have potential impacts for understanding biotic influences on stream channel evolution, stream restoration, and beaver mitigation in North Carolina.

BEAVER DAM FEATURES INFLUENCING STREAM CHANNEL FORM IN THE MOUNTAIN AND PIEDMONT PHYSIOGRAPHIC PROVINCES OF NORTH CAROLINA

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Background

While many studies over the years have created a tremendous amount of factual data, we still have a new frontier to be explored – the connections between these facts. In natural and environmental studies, early naturalists such as Charles Darwin, Alexander von Humboldt, and George Perkins Marsh began assembling these observations, creating the foundation for future studies of ecology. As this field has matured and spread its influence to other disciplines, Geography has taken on many of the studies of ecology, adding the element of spatial relationships. These may take the form of population mapping or movements, distribution, population connectivity, or other overtly spatial studies. However, they may take on another form usually reserved to Geography, that of landscape studies. While geographers have long studied human and animal use of landscape, the study of impacts on the landscape have been largely confined to human impacts, with a passing mention of large grazing animals such as the American Bison, obvious choices such as beaver, and a few scattered investigations of smaller animals such as earthworms. However, as Geography has also begun to mature and find its philosophical niche, more attention has come to the study of animal impacts on the landscape.

This lag is understandable; as George Perkins Marsh pointed out over 100 years ago, humans are the prime agents of landscape change. As we study familiar landscapes, the actions of humans easily overwhelm any sense of other organic change. We recognize the erosion of wind and water, tectonics - the long term physical processes that break down and reshape our world – but the burrowing of a mole, the movement of soil by earthworms, or a treeline trimmed by deer are often lost in the chaos of massive change wrought by bulldozers and chainsaws. In the review of literature we see that since the early 1970s, more attention has come to these small landscape changers, with a slow realization that organisms other than humans have played a major role in shaping landscapes of the past, and many continue to do so today even though their work is seldom noticed. As our society begins to acknowledge many of the biological losses of the past, we begin to understand that these losses resulted not only in the absence of the organisms, but in many cases the loss of landscapes or features associated with them. Enquiry into the grasslands of North America, forests of the Rocky Mountains, the Steppes of Northern Asia, and many other biomes reveal that the habitats we associate with them were formed through biotic interaction with the landscape, and without these biotic factors the landscape will morph over time into a new form, with new assemblages of vegetation and animal communities. Efforts to retain or restore the earlier forms have bolstered the importance of animals in creating and maintaining these landscapes, and strengthened the understanding of the connection between plants, animals, and the landscape.

Predating this understanding, however, was the understanding that some of these landscapes provided services to humans. The value of these services, however, had been overlooked or lost as the Anthropocene period progressed. With this, a new reliance on human engineering to accomplish many of the same tasks previously provided by natural systems became the norm – water filtration plants replaced wetlands with higher volumes of treatment on demand, rotational grazing provided more food than natural herds, and dams provided power as well as flood control. In a sense, we replaced the natural systems with new systems that provided more immediate gratification of our needs, at a seemingly higher efficiency. In the current age of energy concerns, climate change, and dwindling clean water supplies, this reliance in anthropogenic engineering has come into question as these systems invariably require large inputs of energy to build, maintain, and operate. In some cases, such as canalization of the Everglades, the engineered solution to one problem, flooding, has created a host of new problems; land subsidence, sinkholes, and water quality degradation, for which the answers are monetarily costly at best, and elusive at worst. The cheaper solution has been to undo parts of the created system in favor of the natural systems. Though the natural systems may lack the efficiency in flood control that canalization provided, the overall costs are lower due to the range of benefits provided and the lowered cost of operation – nearly free, once the natural system is brought back to a functional state.

Recognition of these ecosystem benefits, as well as aesthetic and moral concerns over the loss of natural habitats, eventually led to the field of restoration. Generally, streams received the earliest attention, with accounts of restoration going back to the 1600s (Montgomery, 2004). Forests and fields followed slowly, as civilization and agriculture began to leave larger areas wither unable to accept rainfall or prone to erosion and loss of topsoil. However, as Montgomery (2007) points out in “Dirt,” erosional losses of cropland were noted by the Greeks, perhaps giving terrestrial habitats the distinction of being the first to garner attention (though apparently little was done about it.) Stream restoration is now a multi-billion dollar business in North America and Europe, with goals ranging from functional restoration (rehabilitation) to comprehensive aesthetic and habitat plans aimed at recreating the lost natural system. Similarly, forests, fields, wetlands, and other habitats are now being restored or rehabilitated to perform a variety of their previous services. Often, though, the difficulty is not merely to restore or rehabilitate; it is the question of restoration to what? What point in the past are we striving to recreate? On the East Coast of North America is it the scenario of incised streams from the 1950s, resulting from 250 years of European-style agriculture, the pre-European contact condition, the early Holocene, or pre-human conditions of over 16,000 years before present? And if we choose those earlier periods, where are the reference reaches to inform our goals? Given the difficulty of these questions, often the decision is made to proceed with rehabilitation instead of true restoration. The stream provides flood control or attenuation services; it provides habitat for some aquatic and terrestrial species; it provides a stable bank and channel, avoiding conflict with human structures, and it provides a pleasing “natural” setting or scenery that appeals to passersby and users of the area. In a sense, it becomes a product of continued anthropogenic engineering, with planned functionality and appeal. Boulders are placed, banks stabilized, vegetation planted, and a static scenario is created to provide the desired outcome(s).

Rewilding

At the other extreme of recreating natural systems is the concept of Rewilding. This concept was introduced, though not under that name, in 1967 by MacArthur and Wilson in The Theory of Island Biogeography, and advances the idea that ecosystems and landscapes are not just patches of static assemblages; rather, they are created by the assemblages themselves over large areas. The most extreme form of this approach is Pleistocene Rewilding (Martin, 2005), which proposes a pre-human restoration of some areas through the reintroduction of species gone for thousands of years, or of their proxies if the appropriate animals are extinct. Examples of this include restoring a large prairie grassland in the American West (Martin, 2009), with the reintroduction of not only bison but also elephants, lions, and cheetahs to replace extinct species

(Flannery, 2002); the re-creation of a native and proxy assemblage in Siberia to restore and maintain steppe habitat (Zimov, 2005), and reintroduction of native and proxy animals into the Scottish Highlands to restore Pleistocene habitat (Browne, 2011.) This last project is a particular interest as the first species to be reintroduced is the European beaver (*Castor fiber,*) currently undergoing a 5 year trial reintroduction. The beavers' role as a keystone species for habitat creation made their presence a priority, as this step lays the groundwork for future species' successful reintroduction. However, the process through which beaver create habitat can both create a scenery devoid of aesthetic appeal to most of the population, and bring the beaver into conflict with human interests, such as roads, culverts, and fruit orchards; these scenarios have made the reintroduction contentious, and no final decision will be made until the end of the trial in 2014.

Thus, human intervention in habitat processes runs from rehabilitation to achieve desirable ecosystem functions and aesthetics on short stream reaches, to setting aside thousands of acres for the reintroduction of ecosystem assemblages and letting natural forces guide the process with uncertain outcomes. Arguably, any efforts suffer from a degree of uncertainty, as we lack comprehensive understanding of all the factors which may come into play during or after our efforts. Chaos theory certainly will come into play during these efforts – the smallest of changes may have unforeseen results. We know little about the effect of aquatic invertebrates on waterflow and friction, or how their bioturbation affects sediment transport; doubtless, the individual effects are small. However, these effects, small as they might be, may be multiplied through the system, or they may be completely lost in the noise of other factors. Restoration remains a somewhat experimental exercise at this point, regardless of the scale at which it is undertaken.

Other efforts to influence our surroundings are also largely experimental, including the introduction or reintroduction of organisms to the environment for economic or aesthetic reasons. Starlings (*Sturnus vulgaris*), introduced to North America in celebration of Shakespeare's works, have proved damaging to both crops and native birds. White-tailed deer (*Odocoileus virginianus*) were re-stocked in many states, including North Carolina, to bolster thinning herds in the 1940s and 1950s; while providing recreational opportunities for hunters and a top browser in forest ecosystems, this has resulted in large numbers of auto accidents and conflicts with other human interests in urban areas. North American beavers (*Castor canadensis*) were reintroduced into North Carolina during the 1930s to provide an economic resource for rural families and thrived, now being present in at least 90 of the 100 counties of the state. While the economic benefit was (and is) negligible in terms of fur, the impacts have been considerable in terms of economic losses through timber, crop, and infrastructure damage, and habitat gains through creation of wetlands and border areas as well as modifying stream morphology. While the merits of their reintroduction can be debated, their presence and effects cannot – they are once again a part of the landscape, exercising their role as a keystone species and altering the environment.

Biogeography

Biogeography has an important role to play in restoration efforts, a role which has been neglected in the past but is gaining recognition with the understanding that “natural” areas are more than an arrangement of physical and biotic features; they are dynamic systems with many levels of connectedness. Hupp et al (1995) discuss the emerging field of biogeography, noting that the term was coined in 1988; a latecomer to the fields of both ecology and geomorphology. Viles (1988) introduced the term in a volume of essays titled Biogeomorphology, which approached the subject from the geomorphology aspect. The various papers and essays presented in the book noted that on almost any surface, organisms of various sizes either resided or temporarily utilized the space; thus geomorphologists should take note of such activity and incorporate it into their studies. Further, they note that biological influences are often difficult to monitor or quantify, leading to their neglect in morphological studies. In the same year, Naiman (1988) wrote that, “Large animals are more than passive components of ecosystems,” a statement echoed by Ripple et al (2014), who point out that removal of carnivores may impact stream form through herbivore overpopulation and consequent riparian vegetation loss. While trophic studies have generally focused on the living ecology of systems in the past, it is becoming apparent that landscapes are also impacted by changes in the populations of animals. In studying the landscape, we must now reconsider some past assumptions on the direction of impact: Did the Great Plains of the American West produce evolutionary pressures that resulted in the American Bison, or did the American Bison exert physical pressures that shaped the Great Plains? At what levels did each affect the development of the other? While such questions regarding the past development are valuable for understanding processes that molded the landscape, there are current scenarios of similar situations which will affect the future development of the landscape. One regards the proposed reintroduction of European Beaver (Castor fiber) to Scotland. Though historically present, they were extirpated over 500 years ago, and part of the debate regarding reintroduction is, after a 500-year absence, is the landscape prepared to accommodate them? Or, will it resemble the introduction of an exotic species that will significantly alter current ecosystems and landscapes that have evolved in their absence? Another scenario currently unfolding also involves beaver, this time the North American Beaver (*Castor canadensis*) and an unintentional release in Tierra del Fuego, South America, in the 1950s. In this case, native plants and other components of the trophic system are not evolved to withstand the beaver's activities, and the beaver are in the process of reworking the entire island's ecosystem. Native trees, unable to resprout from trunks and root systems, are being replaced by invasive species that can survive the conditions imposed by beaver. In this unplanned experiment, we are watching a single species reshape the ecology and landscape of a large area. Free-flowing streams have been replaced by bogs and beaver ponds, while the loss of tree cover has resulted in increased erosion into those areas. If this process is unchecked, will likely lead to a new paradigm for the island, with new trophic systems and landscapes, and resultant new processes for watersheds and streams. Thus, consideration of animal impacts on the physical environment is far from theoretical; they have impacts on current situations and the decisions concerning them.

We must also address the distinction between the intent of reintroducing a species to former habitat: for anthropocentric reasons (aesthetic or economic value,) restoration reasons (to provide some ecosystem service or function), or rewilding (to produce historic or prehistoric landscapes and trophic systems.) The rationale for reintroduction may influence the scope of any such project, and how it is tied to other projects, but at the core of each is the introduction of an organism that will likely have some impact on its surroundings. In a sense, any reintroduction may be considered a form of rewilding in that the landscape may be altered, either to a previously existing form or a new form based on landscape changes during that species' absence. As rewilding carries the connotation of landscape alteration, it is an important consideration for landscape geographers and physical geomorphologists who have long concentrated on non-living agents of landscape processes. If we contemplate changing the landscape through reintroduction of organisms, we must also accept that those species have played a role in the processes that formed the landscape, and their presence or absence plays an important role in the physical as well as ecological environment.

This basis for further study of beaver impacts on not only the ecology but also the geomorphology is supported by numerous studies. Brown et al (2011) looked at rewilding from a geography viewpoint, and point out that while restoration has been practiced for many years in Europe, it has primarily been focused on anthropogenic landscapes, especially those associated with agriculture. As the concept expands to include rewilding with the intent of restoring or recreating non-anthropogenic landscapes, the impact on anthropogenic features pulls in a variety of factors beyond scientific rationale, and these factors, be they politics or economy-based, may outweigh other considerations. In the case of beaver reintroduction into Scotland, the proposal has been contentious, with a considerable amount of research devoted to the impact. Gurnell's review of beaver impacts (1998) was driven by the need to consider reintroduction of beaver versus the potential damage to the current landscape and anthropogenic features. This review reiterates the oft-stated point that beavers are both ecosystem engineers and keystone species, and points to dambuilding as the primary reason for both designations, as well as the most likely cause of conflict with anthropogenic concerns. Ulevicius et al. (2009) studied the impact of beaver on land drainage canals in Lithuania, noting that some canals have been altered substantially since the restoration of European beaver (*Castor fiber*) in the 1940s. Rosell et al. (2005) go beyond the discussion of beaver modification of local ecology to identifying beaver, both *C.fiber* and *C. canadensis*, as being among the select group of organisms (besides humans) that can “significantly change the geomorphology” of the landscape, with the caveat that beaver impact can vary from site to site.

Biotic Engineering

While these papers begin the transition from seeing beaver as merely ecological engineers to landscape engineers, a more comprehensive view is provided by Lewis and Tricot (2003) with a description of the overall impacts of beaver in the Southeastern United States. In this paper, they note that impacts from basic activities such as tree-cutting, lodge building and damming extend beyond merely creating a pond to modifying water tables, local ecology and habitats, erosional processes, and biogeochemical activity. More specifically, Polvi and Wohl (2013) focus primarily on the role of biotic factors in influencing stream form. In this discussion, beaver are considered not only for their direct activity of dambuilding, but also for their secondary influences on riparian vegetation. They conclude that the presence of beaver over a long term directly influences channel form, and offer a proposed cycle of anabranching streams formed in beaver meadows and incised channels in abandoned meadows. Other than sediment, however, the authors do not point to a specific mechanism for the formation of anabranching channels in the beaver meadows, and their work is confined to the Colorado front range. Walter and Merrits (2008) propose a pre-

European contact model of anastomosing streams, though they provide no mechanism for this form. In this research they found that mill-pond building from the 1600s on buried the original wetlands, but do not account for similar dambuilding activities by beaver, active for thousands of years before European intervention. Elliot et al. (2013) describe research of a deposit of early 1800s subfossil leaves which indicate an early riparian forest community different from the post-contact forest communities, and they insinuate an anastomosed “swamp forest” channel form. However, they also fail to support this thesis or provide a mechanism for it, and the 1805-1810 AD dating of the leaves calls into question just how representative this sample may be of a pre-European forest assembly, as well as the lack of inclusion of possible beaver impacts on riparian vegetation. Hartranft et al. (2011) describe a restoration project in Pennsylvania based on the findings of Walters and Merrits, creating a partially anastomosed channel and tussock sedge meadow, but again lacking a mechanism for non-anthropogenic causation of this channel condition. Robinson et al (2007) do present a well-supported study demonstrating the usefulness of preserved vegetative material in an early Holocene (ca. 9,300 ^{14}C years BP) beaver dam to document climate-related vegetation change. Kramer et al (2012) used ground penetrating radar in Colorado to locate Holocene beaver meadows and quantify the sediments trapped in them, and concluded that between 30 and 50% of valley fill in that setting were due to beaver activity. They further noted that to ignore biotic factors such as beaver is to ignore an important driver of valley sedimentation. As to potential benefits of beaver dams in providing ecosystem services, Pollock et al. (2014) examine the potential of using beaver dams, or analogous structures, to restore incised stream systems. Burchstead and Daniels (2014) offer a classification of the impacts beaver may have on small headwater systems, noting changes including raising the base level of the stream, groundwater levels, vegetation, and altered channel forms below the dams, including multichannel formation. Finally, Butler (1995) devotes an entire chapter to beaver in his treatise on zoogeomorphology, noting that, "More than any other animal except humans, beavers geomorphologically alter the landscape through their dam building and related activities."

Research Questions

The continuing spread of beaver through North Carolina presents an opportunity to augment these studies and refine the understanding of how beavers act as agents of geomorphological change. Given the known date of reintroduction in 1937 places all beaver activity within a specific time range, and the rapid spread allows comparative studies of beaver activity over the range of two North Carolina Physiographic provinces: the Mountain and the Piedmont. A better understanding of beaver dam construction and related activities and structures may allow further understanding of biotic factors of landscape formation as well as insight into how these processes may be used in future rehabilitation or rewilding efforts.

This study will use this opportunity to examine 4 specific research questions for beaver impacts in North Carolina:

1. What is the physical morphology of beaver dams in North Carolina?

    i. Dams are primarily constructed of woody debris.
    ii. Dams are primarily constructed of soil.
    iii. Dams vary according to local conditions.

2. Does beaver dam morphology differ between the Mountain and Piedmont physiographic provinces of North Carolina?

    i. As animals relying on instinctual behavior, there will be little variation in dam morphology in different areas.
    ii. Dams building materials and conditions vary between the two provinces, therefore morphology can be expected to reflect provincial landscape differences..
    iii. Dams vary according to local conditions regardless of which province they are located in and thus no regional generalizations can be made.

3. Can beaver activity explain some aspects of the hypothesized anastomosing pre-European wetland streams described by some researchers?

    i. Beaver activity cannot account for the proposed conditions.

ii. Beaver activity may provide a mechanism for some proposed conditions.

iii. Beaver activity may explain most of the proposed conditions.

4. Are there any effects of beaver activity that might be useful in stream rehabilitation/restoration projects in North Carolina?

i. Beaver impact is too stochastic to provide a useful resource.

ii. Some effects of beaver activity may be useful for rehabilitation/restoration across the entire State.

iii. Beaver impacts may generally be useful in one or more Provinces but not universally across the State.

CHAPTER II

LITERATURE REVIEW

Theoretical Basis

Many existing studies fall into the tradition of biogeomorphology; the multidisciplinary study of how organisms interact with and affect Earth surface processes and landforms. Examples of this include herbivores removing vegetation, dust wallows created by American bison, gopher soil turnover and displacement, and channel modification by beaver (Butler, 1995); crayfish and fish bioturbation of streambeds (Statzner & Sagnes, 2008); tree uprooting and soil formation (Samonil *et.al.*, 2010); and bryophytic accumulation of sediment in pools (McKinney & Jaklin, 2001). Hupp et al., (1995) provide a description of this discipline, tracing its roots to the early 1900s. They note, however, that as the sciences of geography and ecology developed throughout the 20th century, there was little interaction until the 1980s. Allen and colleagues (2003) added clarity to the field by refining the definition of ecological engineering, noting that ecosystems are difficult to define because they are always "becoming in time." As beavers are referred to as ecosystem engineers in multiple sources, this temporal description suggests that studies of beavers' influence will likely not produce a static model, but rather a temporally distributed model of effects which may not have an equilibrium state.

Biogeomorphology is a unifying theme for complex systems (Stallins, 2006). There is also a solid basis for connecting human impacts on animal populations to fluvial changes, with the reduction of beaver in North American being a prime example (Butler, 2006). Corenblit and colleagues (2007) discuss the relationship of biological factors in influencing fluvial morphology, providing concrete linkages between biotic and physical factors that demonstrate reciprocal influences on each other. Beaver dams and their associated environments are complex systems with many interrelated processes, and the following section discusses previous research related to the various impacts related to beaver activity.

History

The North American Beaver, *Castor canadensis*, is a large aquatic rodent native to much of the North American continent (Butler, 1995), and likely present in large numbers before European settlement (Butler and Melanson, 2005). Adults typically weigh 35-50 pounds (15-23 kg.) and may be over 1m long (North Carolina Wildlife Resources Commission, no date.) Settlement brought a demand for beaver hides and destruction of beaver habitat, extirpating beaver in some areas and severely reducing their numbers elsewhere in the eastern USA (Dolin, 2010). In North Carolina, the date of final extirpation is believed to be 1897, with reintroduction in the 1930s (North Carolina Wildlife Resources Commission, no date.) Since their reintroduction beaver have spread through

North Carolina (Townsend and Butler, 1996), and likely occupy all 100 counties or will do so in the near future.

Previous Research

One of the most common types of beaver study examines their foraging behavior. Baccus et al. (2007), for example, studied food preferences in Texas, and concluded that beaver prefer specific tree species, with the most favored size being between 1 and 5 cm. This pattern implies not only ecological impact, but also affects restoration and the choice of species for replanting riparian zones in areas where beaver are active. Species and size selectivity may also be important in actually influencing fluvial changes. Fetherston et al. (1995) concluded that patterns of forest growth and contribution of wood at the >10 cm size have substantial effects on fluvial form. Foraging selectivity may not be constant, and food selection by beavers varies on both a seasonal and yearly basis (Jenkins, 1979). This variation may be due partly to changes in the landscape as preferred trees are depleted; examining beaver foraging behavior as a predator-prey relationships showed that changes in “prey” (trees) abundance and diversity could substantially alter the beavers’ foraging behavior (Fryxell et al., 1994). The nutritional content of bark also changes seasonally, which has a high correlation to the beavers’ seasonal preferences (Jenkins, 1979). Of particular note in this study were the greater seasonal stability in coniferous tree species and the greater year-to-year stability of non-mast bearing trees. Fryxell (1992) also studied the foraging behavior based on spatial distribution of preferred species, and found that at high densities (such as a new dam site) beaver demonstrated random foraging over the areas closest to the water. Patterns evolved, however, as food densities decreased. Sturtevant (1998) created a model of simulated beaver wetlands to investigate vegetative dynamics under a regime of seasonal hydrologic changes. This model indicated that vegetation patterns were dependent on beaver activity, and that the resulting wetland area was sensitive to seed introduction through both flooding and waterfowl dispersal.

Another primary area of study explores the effect of beaver ponds on species diversity. These include animal and plant communities, both aquatic and terrestrial. Ray and colleagues (2001) partially verified Sturtevant's model of high receptivity to seed species introduction. They found that macrophyte succession followed a linear pattern of species diversity in beaver ponds in Minnesota for the first four decades of a pond's existence, and then settled into a mature, more stable assemblage. They noted that the density of nearby ponds that served as donors for species dispersal influenced the pattern; thus, their models may overstate the rate at which new ponds in the southeast develop macrophyte diversity due to the much lower density of beaver ponds. Beaver meadows and their plant assemblages may result from the abandonment of dams; these previously flooded areas lack the ectomycorrhizae fungus necessary for successful conifer growth, resulting in exclusion of conifers from the meadows until burrowing mammals reestablish the fungus (Terwilliger and Pastor, 1999). This creates an exclusionary vegetative zone exploited by species not reliant on the fungus, generally grasses and sedges in the study area in Minnesota; otherwise, these species would likely be out-competed by shade-producing conifers.

Animal diversity is influenced as well, in terms of both communities and specific animals. Both Snodgrass and Meffe (1998) and Hagglund and Sjoberg (1999) determined that beaver ponds influence fish species and size distribution in streams. Snodgrass and Meffe, working in the piedmont of South Carolina, found both the size of the pond and watershed influence species diversity. They also determined that diversity increased to a high point within the pond over the first nine to 17 years, but was always lower than unimpounded stream reaches. Their study concluded that beaver ponds decrease fish diversity due to higher water temperatures and lower dissolved oxygen levels. Hagglund and Sjoberg, however, reached slightly different conclusions in Sweden where beaver ponds changed the number and size structure of fish composition in the affected areas, but not diversity. There may be some positive effects on aquatic life; despite lower overall diversity, the ponds may serve as source areas for both fish and invertebrates (Schlosser, 1995).

On the other hand, the diversity of some species has benefited from beaver ponds. The ponds may have a significant positive impact on otter habitat, and could be a major factor in determining otter dispersal (LeBlanc et al. (2007).

Beaver ponds mitigate and smooth the effects of seasonal climate variations in western Canada (Hood and Bayley, 2008). Here, the presence of beaver ponds exerts a greater influence on the survival of wetland conditions than does temperature, precipitation, or other climatic variables. This finding supported Stevens et al. (2007), who determined that beaver-created wetlands are suitable surrogates for the presence of a diverse amphibian assemblage due to creation of stable wetland areas. Edwards et al. (1999) also found increased bird diversity around beaver ponds in the South Carolina Piedmont, and attributed it to the increased diversity of habitat, especially in the form of standing dead trees, snags, and shallow wetland areas.

Studies of beaver influenced changes in water chemistry returned mixed results. Downstream levels of nutrients, for example, are increased under some conditions (Maret et al., 1987), while in other settings they are decreased (Correl et al., 2000). Groundwater levels often increase, as does the rate of evaporation and transpiration (Correl et al, 2000.) Additionally, beaver ponds are often shallow and exposed to full sunlight, conditions that encourage periphyton growth which enhance nutrient cycling rates. Cirmo and Mcdonnell (1997) found that nitrogen retention, cycling and transport in forested areas was largely dependent on the terrestrial/aquatic boundary zone of saturated soils; these areas increase in beaver ponds with their larger boundary areas. Sediment community respiration is much higher in lakes with high surface areas and full sunlight than in forested streams (Hedin, 1990). In beaver-influenced habitats, creation of these same conditions may play an important role as sunlight drives the primary production (and thus nutrient cycling) in ponds (Brőnmark and Hansson, 1998). When measuring other parameters of water quality, Burns and McDonnell (1998) noted that longer retention times of water behind beaver dams resulted in more efficient neutralization of acid precipitation in streams that had been treated with calcium carbonate, suggesting that they play a beneficial role (in concert with remediation efforts) in improving this aspect of water quality.

Beaver dams and sedimentation influence nutrient cycling, but their influence extends beyond water quality to directly affecting the morphology of both the pond and the downstream area. Meentemeyer et al. (1998) found that beaver in one North Carolina stream actually increased erosion above the dam area, adding sediment to the pond; thus beaver impacts included both mobilizing and storing sediment in the same stream reach. Work by Butler and Malanson (1995) discussed the rate of sediment trapping by beaver dams, and found it to be quite high. Later work by the same authors (2005) investigated the impacts of pre-European beaver dams in North America. In this research, they estimated between 15 million and 250 million beaver ponds existed, with a sediment storage range between 3 billion m^3 and 50 billion m^3, though they do not indicate if this includes the dams or only the storage areas behind the dams. With the loss of beaver population some of dams failed, releasing sediment and perhaps fundamentally altering the fluvial state of streams over time. The presence of these dams, even on the low end, must have had a profound influence on the landscape; when Bishop Spangenberg traveled through North Carolina in 1751-1752, he noted that the party sometimes had to avoid beaver-infested, swampy areas along creeks and stick to ridgelines with their horses (Fries, 1922). This provides an interesting comparison to the work of Walter and Merritts (2008), who concluded that the construction of thousands of mill dams in the 17th, 18th, and 19th centuries, along with agricultural practices of the time, created the step-plain topography seen in the Piedmont and Coastal Plain regions of the Mid-Atlantic Coast of the United States today. They further concluded that these sedimented ponds covered the original morphology of the streams, which they believed were not meandering valley streams, but anabranching streams flowing through wetland areas.

Gurnell (1998) also examines the issue of beaver-influenced fluvial change while examining the potential effects of beaver reintroduction in Scotland, where they have been absent for over three hundred years. Though European beavers (Castor fiber) appear less likely to build dams, she notes that they may still have extensive geomorphological effects through burrowing and tree cutting, and these may have some consequences for human activities in beaver influenced areas. Hartman and Tornlov (2006) also examined the habits of European beaver dambuilding activities to establish thresholds for river sizes above which beavers would not attempt dambuilding activity; they noted a mean depth of .36 meters and mean width of 2.5 meters at dam sites, and a mean water depth of 1.16 meters and mean width of 11.15 meters at lodge sites lacking a dam. Beier and Barrett (1996) found that active beaver colonies in the Truckee valley in California had a mean stream depth of 2.44 meters and a mean stream width of 8.1 meters, and Carpenedo (2011) based the likelihood of beaver occupation on valley size and gradient rather than stream size. Howard and Larson (1985) used gradient as the primary geomorphological variable, but found a mean stream width of 2.85 meters in their study. This variation in both result and method indicates that consensus may be lacking in threshold values for dam building, and may vary regionally, necessitating local calibration to determine the likelihood of beaver activity.

Anabranching Streams

Anabranching streams, such as those proposed by Walter and Merrits (2008) as a pre-European condition in the eastern USA, remain a difficult area for geomorphology, both in classification and identification of mechanisms leading to their formation. Makaske (2001) offers the following definition: "an anastomosing river is composed of two or more interconnected channels that enclose floodbasins," and states that the process is driven primarily by avulsions. As both anastomosed and anabranched streams share many characteristics with a somewhat indefinite boundary, this paper will use the term anabranching so encompass the possible variations of stream form encountered at dam sites, while not excluding that some of these channels may resemble anastomosed channel forms by some definitions. These avulsions are attributed to loss of channel capacity due to in channel deposition. Other events may affect this process, including extreme floods, ice/log jams, and aeolian deposition. Caring et al. (2012) disregard this simple definition, pointing to the difficulty of defining what terms are appropriately used to define multi-channel systems, and that the continuum of forms, and the various processes which produce them, make accurate descriptive terminology difficult. The mechanisms leading to anastomosing have generally been approached from a physical process paradigm, tending to focus on deposition, hydraulic processes, and avulsion as primary agents in their formation. (Makaske et al., 2009; McClenagan 2013; Bernal et.al, 2013).

Pollock et al (2014) offers a slightly different approach by proposing beaver dam analogues to restore incised stream areas, taking the eventual production of anabranched streams as a given result of sedimentation and the creation of a “high level of complexity” develops in the pond area. This approach recognizes the biotic influence on the creation of anabranched channels; however, they do not examine the individual components of this complex system, and place emphasis on Beaver Dam Analogues (BDAs) to trap sufficient sediment to raise the incised stream channel enough to approximate pre-degradation conditions, including anabranching.

Vegetation, however, has been identified as an potential influence as well, with Gradzinski et al. (2003) stating that, “The impact of vegetation on the system is overwhelming.” In this example, a peat substrate resists avulsion and is stabilized by heavy vegetation, though during high flows this same vegetation may create channel blockages leading to a slow avulsion of new channels. The effect of vegetation extends to the effects that peat may have in controlling channel form (Watters and Stanley, 2007; Banasuk, 2011), indicating further recognition of biological inputs in some anastomosing processes. Providing further evidence for the role of vegetation in influencing channel form, Wohl (2013) states that evidence of anastomosing streams first appears in the Carboniferous Period, indicating a connection between anastomosis and vegetation large enough to block channels. Gendaszek et al. (2012) followed historical changes in the Cedar River, Washington, USA, and noted that flow control, with a subsequent reduction of sediment load, and removal of large woody debris (LWD) sources, resulted in the formerly multi-channel stream bed narrowing to a single channel in many cases. However, they also noted that unconfined reaches long enough to allow for sediment and LWD recruitment maintained a high level of heterogeneity (including multiple channels), even with reduced flows, thus giving vegetative influence an impact on par with non-biological influences.

As beaver have returned to many areas both in North America and Europe, there have been observations pointing to potential biogeomorphological influence they may have on stream form, including anastomosis (Burchstead et al. 2010, Polvi and Wohl, 2013; Burchstead and Daniels, 2014). Nyssan et al. (2011) state that anastomoses is frequently noted on beaver-dammed streams in areas of Germany due to the diversion of water onto the floodplain downstream of the dam, providing a connection between physical processes and an active biological component, the beaver. Implied in this connection is the influence of vegetation, albeit indirectly, in the form of food and dam-building material.

Considerations

Based on the many aspects of beaver activity, a brief discussion concerning beaver and their habits is appropriate before a broader discussion of the observations of this study. Beaver, though a keystone species, act instinctually to provide themselves with food, shelter, and protection; this is accomplished by modification of their environment. Cutting trees, shrubs, and herbaceous material is a foundation of beaver existence, as these materials provide the resources for both diet and habitat alteration.

Wood, provides food and building material for the dam, which in turn floods the riparian zone (and beyond), providing access to more wood in a sort of ecological capitalism based on continued growth. This pattern can be interrupted in several ways. The first, most predictable manner is pond size reaching a limit of gradient on the valley walls where continued dambuilding produces little additional access to woody material. The dam may become high enough to lose stability and be more prone to damage by flooding, or the beaver may abandon the pond and move to fresh areas to begin the process anew. The second situation involves loss or partial breaching of the dam, wherein the pond level drops and moves away from resources. Rebuilding is dependent on access to food to last long enough to rebuild the dam and continue the growth of the pond. As observed at site P1a, beaver are quite efficient at repairing dam breaches, and are quite likely to attempt rebuilding if food resources are available. Predation may be a problem from animals such as bears or coyotes, and for smaller beaver, wildcats, but many areas of North Carolina lack predators numerous enough to threaten the beaver population to any great extent.. Suitable sites have a strong draw for beavers, as evidenced by the cycle of beaver removal and repopulation at site C1. The final situation is predation by either natural or anthropogenic means, which leaves the area only partially expended of resources. In cases of anthropogenic removal, dam breaching often occurs as well, allowing the site to begin new growth of woody material much sooner than leaving an inundated area which retards tree growth.

Beaver utilize nearly any woody material for food, though may have preferences when certain species are available. Specifically, the outer and inner barks provide nutrition, leaving the inner wood trunk as discard material. This may be utilized for dam or lodge construction, remain on the land where it was felled and stripped, or come to rest in the pond, either randomly or in discard piles. In addition to this beaver-produced woody material, LWD coming from upstream are trapped in the pond, as noted in all Piedmont and Coastal Plain sites, and trees that have been inundated and died before consumption may remain standing over a long period, slowly adding to the total accumulation of the pond’s wood budget.

Herbaceous materials, grasses, sedges, and forbs, are also resources for food and dam building, and are the first vegetation to colonize abandoned ponds as the water level decreases. Butler and Melanson (2005) describe the large volume of sediment trapped by beaver ponds; this sediment forms a favorable environment for quick growth of this material, though some trees may take much longer (Terwilliger and Pastor, 1999.)

Finally, beaver are instinctual animals; their behavior is based on innate behavior, and perhaps some learned behavior, but they lack human foresight and planning facilities. Sites may be selected because of an excellent setting, or may be selected because it is the only area available due to other beaver or anthropogenic activities. Food is a first priority, and where there is food, beavers can survive and attempt a dam regardless of site conditions. A former beaver control agent related the story of a pair of beavers attempting to build a dam on a tidal slough in coastal North Carolina: he noticed the construction during low tide and was intrigued; he continued to observe the site over several days. During low tide periods the beaver would begin construction, but each high tide swept away the previous work, leaving the site bare. During the next low tide, the beaver would begin rebuilding. This cycle persisted for approximately a week before activity ceased, presumably due to the beavers giving up and moving. (Neuman, pers. comm., 2013.) This provides a poignant cautionary note to assuming that beaver instinctually locate the best sites; a dam may be attempted nearly anywhere the beaver have food to sustain them.

With these considerations, beaver dam building must be considered a very different situation from human dam building. While materials are sometimes the same, needs and intentions are very different, and the eventual outcomes may differ substantially. Anthropogenic dams are considered long-term investments, often without consideration of the final outcome; beaver dams are fated to a finite life, based on expansion until no returns are realized.

Past these resource considerations is the actual purpose of the dam. Unlike mill dams or most other anthropogenic dams, beaver have no need for depth, large volumes of water, or a good gradient for generating mechanical force; nor are they concerned with water quality. Beaver need only enough depth to provide transportation and protection, and a low gradient environment is much more suitable for dam building and continued expansion to reach new resources. As mammals, water quality, in terms of dissolved oxygen levels, dissolved/suspended materials, and temperature, have little effect on them. Another major difference is that anthropogenic dams are general static with an established water extent, whereas beaver ponds rely on continued expansion to provide resources – the water is not a resource by itself; it is the access and protection provided by water that is key to beaver function.

One note is in order before proceeding to the discussion proper: all activities and structures are discussed in the context of non-anthropogenic intervention unless otherwise noted. While the activities in North Carolina occur in the context of anthropogenic landscape modification, intervention in the form of removal or intentional dam breaching obviously breaks the progression of events in development.

CHAPTER III

STUDY AREA

Study Area

As North Carolina consists of three physiographic provinces, Mountain, Piedmont, and Coastal Plain, part of this study was to investigate beaver sites over a large enough area to allow some comparison (figure 1). The primary focus was the transition between Mountain and Piedmont Provinces, as the Blue Ridge Escarpment provides a rapid transition between these two regions. Each province provides both different terrain and forest composition, creating different conditions for dambuilding. The Mountain Province is composed of areas of high elevations (up to 2,037m) and dissected terrain, with the greatest topographic relief east of the Mississippi River. Streams are generally high gradient, with woody vegetation primarily consisting of hardwood forests, and, at the higher elevations, spruce/fir forests. Average rainfall is approximately 1500mm/year, with temperatures averaging 18°C in summer and 6°C in winter. The Blue Ridge Escarpment provides a sharp transition to the Piedmont Province, with much lower elevations (100-500m) and correspondingly lower stream gradients, which begin to attenuate the sediment load produced in the Mountain Province. Average rainfall in this area is approximately 1,150 mm/year, with summer temperatures averaging 21°C and winters averaging 9°C. Woody vegetation consists of mixed hardwoods, with a transition to bottomland hardwoods and coniferous stands. The Fall Line marks a drop in elevation to the Coastal Plain Province, with an average yearly rainfall of 1,200mm, and an average summer temperature of 22°C and average winter temperature of 11.5°C. Stream gradients are typically quite low, with elevations ranging from sea level to 150m. Woody vegetation in this province consists primarily of bottomland hardwoods and conifers.

This study consisted of seven sites in the Mountain Region of North Carolina (Sites M1-M7), 4 sites (sites P1-P4) in the Piedmont, and 1 on the Coastal Plain (site C1). Each was visited multiple times over the course of the study, and in total represented 51 main dams, 67 check dams, and 9,910 total meters of stream impacted. Of these sites, 5 were abandoned over the study period, 2 were abandoned before the study period (1 identified through remains, one based on prior knowledge,) and 8 remained active. Longevity ranged from 3 months to 19+ years, with older sites developing into strings of dams (up to eight in one location) along the stream. Complete descriptions of these sites are found in Appendix A.

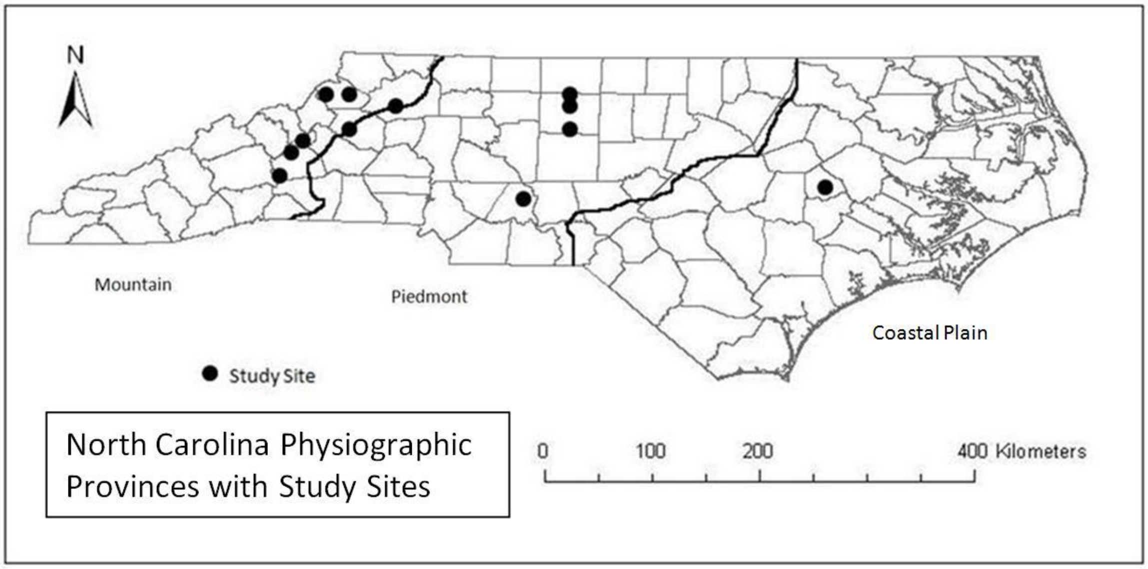

Figure 1. North Carolina Physiographic Provinces with Study Sites. (Author)

Site Selection

This research was designed to investigate both the physical structure of beaver dams and identify features and functions specific to the dam itself. While the dam does result in a pond and numerous ecological and physical effects resulting from the pond, those areas have been studied extensively in the past. Here, the focus was on the dam as a landscape feature: extent, volume, and local influence. As this study was founded on the concept of biogeomorphology and how reintroduction of organisms or rewilding of areas may affect our understanding of biotic influences on the landscape, the first step in investigation was to visit numerous sites to better understand the physical setting and parameters of the dam, and see what presented interesting or unanswered questions. After this initial phase, a literature search was performed to find previous research pertinent to questions developed during the observation phase, and the specific questions for this project were developed to address areas not covered in prior research, or not addressed for the regions of North Carolina.

Sites were identified through local contacts and visual inspection, and were mixed between public and private lands. Landowner permission on private sites proved easy to obtain, as was permission to access some otherwise off-limits areas of public lands. All were enthusiastic about aiding the research, with two landowners providing equipment to aid research on their property. Attitudes varied across the spectrum, from leaving the beaver alone, to taking minimal action to prevent impact to anthropogenic interests, to a desire for total removal regardless of impact.

Site verification consisted of an exploratory trip to the site to determine accessibility and equipment needed, followed by another trip to document variables for this study, and follow-up visits were made to each site over the course of the study to verify information and observe any major changes, such as abandonment.

Several sites were examined but discarded for this study due to direct human involvement in ongoing activities, making it impossible to differentiate between beaver impact and anthropogenic impact; the sites chosen represent areas with little to no human involvement in landscape or stream modification, though partial or complete removal of beaver through trapping did occur at several sites over the course of the study.

CHAPTER IV

METHODS

Overview

Beaver dams in North Carolina often pose a challenging environment for data acquisition. Many are located in heavily vegetated areas, inundated with water, and the ponds themselves are filled with pointed stakes resulting from beaver cutting trees in the area before inundation. Additionally, ponds are typically filled with leftover woody debris, varying from small sticks to larger lags, and may contain food stashes of tangled branches. Canals left from previous forays and submerged by continued damming and subsequent water elevation, create sudden drop-offs which may be as much as a meter deeper than the surrounding area. It was discovered during this scouting period that the upstream face of most dams are extremely difficult to traverse due to loosely packed materials (unconsolidated soil) and the propensity to slide into deeper water. Beaver ponds are also well-recognized for their rich species diversity, and though most organisms pose little threat, the chance of encounters with venomous snakes was elevated working in these areas.

Given these conditions, initial preparation involved scouting research sites to understand the challenges involved, both for safety and research. In addition, several professional trappers provided advice on working in this environment, and Dr. Walt Gibbons of the Savannah River Ecology Laboratory provided invaluable advice on avoiding encounters with venomous snakes, and appropriate actions to take if such an encounter occurred (Gibbons, 2011). While clothing is not directly a part of research, it does affect how research can be done and influences methods. For this study, standard gear included thick neoprene waders with a large pair of denim overalls worn over them to provide protection from briers and tree stubs. A personal floatation device was also worn in most areas to provide protection from encounters with underwater canals and other unplanned submergences.

Procedure

Dam size was determined using the stadia rod, tape measure, laser rangefinder, and L-rod as appropriate for each location. Distance between dams was measured, most often with the laser rangefinder. Surveys of the downstream dam faces were conducted to determine the number and location of flowing water outlets large enough to create identifiable channels. Where allowed, sampling of the dam was conducted using post-hole diggers to determine the composition of the dam. Maximum pond depth was determined through either stadia rod (wading), L-rod (from the dam), or sounding line (from kayak.) Photographs were taken throughout the process to document topography or notable features.

This field data was then used to calculate dam volume for each dam individually, as well as a total volume for material at each site, and mapped to provide location of notable features such as channels below the dam. Using GPS data the dam location was identified digitally using ArcGIS 10 from Earth Sciences Resource Institute and 20 foot lidar elevation grids downloaded from the North Carolina Department of Transportation. Sites were then processed to calculate drainage area and valley floor slope for each location. In the event multiple dams were present, these values were calculated for the first and last dam on the stream reach.

Channel type was evaluated according to the Channel Evolution Model presented by Shumm et al (1984), figure 2. In this classification, Incised streams, where the main channel has degraded and lost connection to the floodlplain is Type I; inn Type II the stream has widened and regained a limited floodplain, though still confined and not well-connected to a full floodplain, and Type V has aggraded sufficiently to have a connected floodplain.

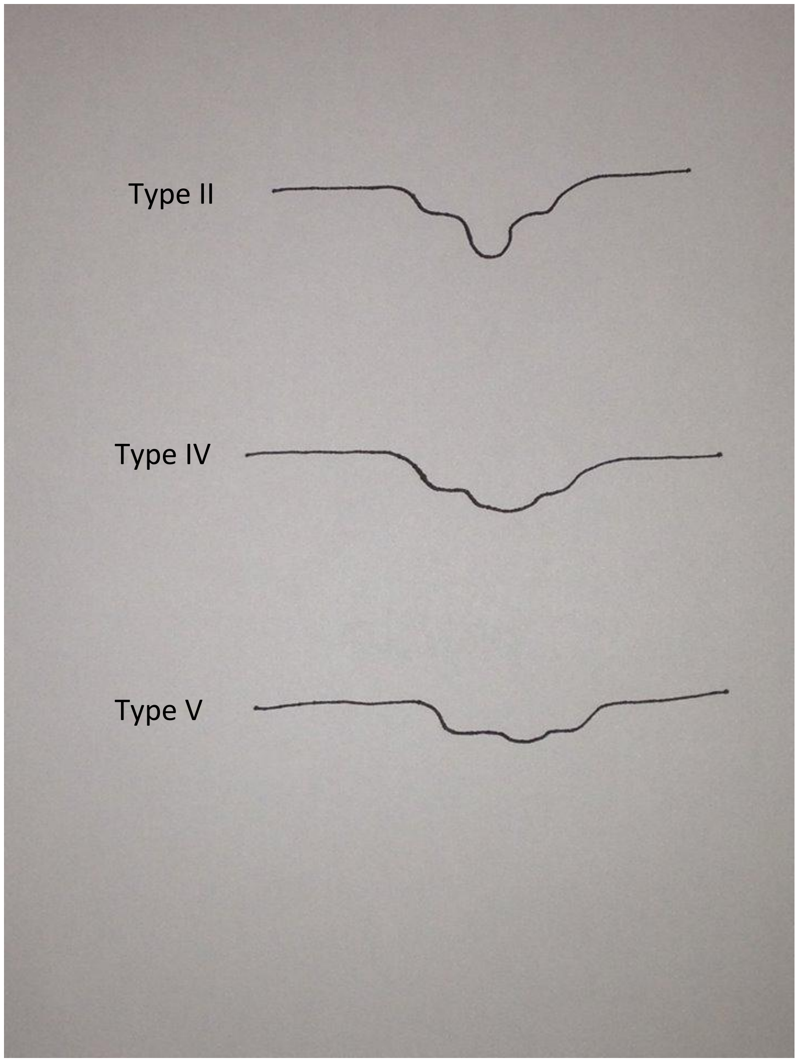

Figure 2. Channel Types. (After Shumm et al, 1984)

Field data was organized to describe the observations at each site (Table 1.) This was analyzed using Microsoft Excel spreadsheet with the data analysis pack to produce both graphs demonstrating linear regression, and Pearson's correlation coefficient R as well as well as r^2. Pearson's R was then plotted as a matrix (Table 2) to determine which, if any, relations provided useful insight into the interaction of variable features in the dam site, Correlations at the r^2>.40

value, with α=.05, were examined in conjunction with field notes, aerial imagery, and natural history information pertaining to beaver to discuss site development, features, and possible outcomes.

Observations and Variables

Impact Length

Length impacted is the total length of channel affected by beaver activity, and is the length from the downstream-most dam to the uppermost limits of impoundment. This was accomplished though the use of on the ground measurement using the laser rangefinder where possible, and through measurement of orthoimages where impossible to accurate measure on the ground.

Watershed Area

Watershed area was calculated using ArcGIS 10.1 and USGS NED 1/9 arc-second DEMs, USGS NHD Dynamic extract maps for hydrology, and USGS Topographical maps for reference. These values represent the total basin area from the most downstream main dam at a site.

Main Dams

Main dams are defined for this study as any dam which is built in the primary channel to create a pond, and raises the water level.Beaver dams may vary considerably from location to location, but can be generalized into three different categories: Sticks and Stones, Wattle and Daub, and Beaverlith. These construction types are dependent on the availability of local resources, and more than one type may be found in a site that contains multiple dams over a long reach of stream. Typically, the sticks and stones dams are found in confined, high gradient reaches with little or no clay or loamy soils adjacent to the dam site; wattle and daub are found at lower gradients where some soils are available, and Beaverlith dams are found in low gradient streams where soil is readily available at the dam site. Each represents use of the available materials to create a dam, and thus mixing of types represents a transition in resources. For example, no examples of sticks and stones were found mixed with Beaverlith, though wattle and daub was found mixed with Beaverlith.

Construction

Construction was identified as falling into one of three general categories, depending on available resources; these were Sticks and Stones, Wattle and Daub, and Beaverlith.

Sticks and Stones dams are built primarily of woody material with stones throughout. Vegetation, primarily leaves, are added or become tapped, and act as filler in the lattice, as does some courser soil, but in limited amounts. These dams, even when active, typically have multiple outlets due to the unfilled areas of the wooden lattice. During the course of this study this construction proved the most fragile, as all were washed out in less than two years. Two other locations of previous dams of this type were noted and identified through local residents, and in sites M2b, M5, M6, and M7, noticeable stone deposits were left across the streambed after the loss of the woody material. These formation were dispersed after 3-5 months in M2b and M5. Sites M6 and M7 were discovered after the woody components were gone, but the cobble accumulation persisted for over a year after initial discovery. It is not know if the stone accumulation was due primarily to beaver activity or the trapping action of the dam, but likely, the bulk of cobble-sized material was collected through trapping. It is quite possible that the material has both an armoring effect of the stream bottom, and also Manning's coefficient, which raises the possibility that the beaver activity may continue to affect the stream channel for some time after the cessation of activities. This is especially true in instances where beaver have denuded the bank during the active phase, leaving it more vulnerable to stream activity influenced by the remaining cobble.

Figure 3. Sticks and Stones Dam. (Author)

Wattle and Daub dams represent the classic idea of a beaver dam, with both woody material and soil. Construction is very similar to early house construction using a wooden lattice (“wattle”) woven closely enough to support soil material (“daub”) applied to it. These dams may also have stones embedded erratically, but they do not form a continuous structural element through the dam. These dams represent a transition in available materials, and are typically found at lower gradients than the sticks and stones dams. These were not noted to form a significant accumulation of cobble, possibly due to lower stream energies at lower grades.

Figure 4. Wattle and Daub Dam. (Author)

Beaverlith dams rely on the presence of available soil, and forms an earthen construction quite similar to adobe. Several excavations of beaverlithic dams provided insight into the construction of this form of dam. A bottom layer of woody material, similar to the lattice of the wattle and daub construction forms a dam nucleus, though it contains more herbaceous material (figure 5.) As the dam grows, construction transition to primarily earth and herbaceous material, with small amounts of random woody material interspersed. Food discard woody debris is pushed over the top, forming a wooden layer on the downstream face. The upstream face is primarily a soil/vegetation mix with little woody material.

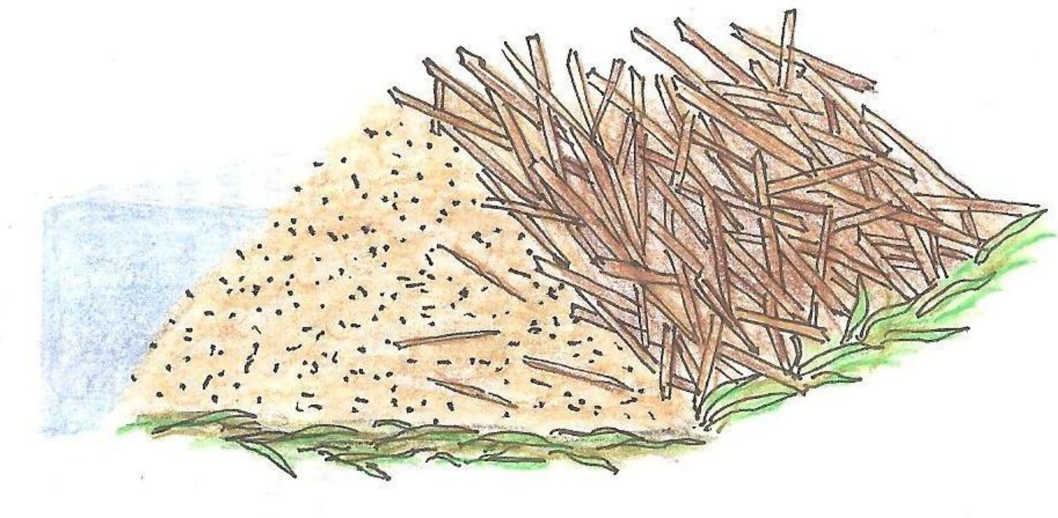

Figure 5. Generalized Beaverlith Construction. (Author)

Several experiments were carried out on this type of construction to better understand it. The first was opening a small 30cm wide x 15 cm deep (below pond level) gap in the primary dam at the P1a site to observe erosion of the dam over time. The sides and bottom eroded approximately 3 cm over a 30 minute period, but after that time erosion ceased, and no further erosion was noted over the next 4 hours. Inspection revealed that the herbaceous material, as it become exposed by eroding soil, folded downstream, effectively armoring the sides and preventing further erosion. This experiment was repeated three more times at different locations on this dam, and 2 times on the primary beaverlith dam at P1b with similar results. 2 tests at site C1 yielded consistent results as well. It appears that the inclusion of vegetation in the dams not only provides bulk and structural integrity (as adobe), but also creates a system that limits damage from erosion in the event of small breaches.

Another experiment at P1a provided documentation that the inclusion of vegetation was not incidental to the packing of soil onto the dam. A 1 meter wide by .5 meter deep breach was introduced into the dam, and an infrared camera trap installed to monitor activity. The progression of rebuilding was photographed, with figure 6 showing initial foundation work of small woody material, figure 7 showing grasses/sedges being added, figure 8 showing wet soil being packed on the structure, and figure 9 showing the finished patch the next morning. Note the lack of any large woody material during the construction process; however, by the next morning several pieces had been pushed over the top onto the downstream face of the repair. These were later covered over by the inclusion of more soil and herbaceous material as the patch was worked on over the next several weeks, but always with the same pattern of woody material being pushed over the dam.

Figure 6. Beaver rebuilding Dam Section, Foundation Section. (Author)

Figure 7. Beaver rebuilding Dam, adding Herbaceous Material. (Author)

Figure 8. Beaver rebuilding Dam, packing with Soil. (Author)

Figure 9. Beaver rebuilding Dam, Finished. (Author)

Although I was not able to document any high flows that overtopped these dams, it is likely that the woody material on the downstream face acts as armor against erosion when water flows over the dam. I did find extensive evidence of leaves, grasses, and small sticks tangled in the wood, apparently as a result of water flowing through the woody matrix.

Based on the construction at sites containing both wattle and daub and beaverlith, it was apparent that Beaverlith was the preferred method of construction when soil was readily available; for example, in site P1a, the wattle and daub dams were only found in an incised section of stream running on bedrock in a heavily forested area. Little soil or alluvium was available to be scooped from the bottom, and excavation from the banks was limited. The 3 lower Beaverlith dams were located in a wide area previously used as an agricultural field, with the original streambed connected to the floodplain and thus a readily available source of soil.

Beaverlith was also noted in several lodge sites, both as a foundation and covering material. Though unable to examine these sites closely due to beaver activity, construction appeared to be much the same as the dams with the exception of woody material covering them.

Check Dams

Check dams are small dams filling low areas in the terrain or otherwise diverting water to keep it within the main pond area. These were typically between 1 and 3 m in the study sites; beyond that they generally joined and became part of the primary dam. Construction typically mirrors the primary dam, though being much smaller the base woody debris lattice constitutes a larger portion of the dam material. These dams are closely associated with anabranching channels in the downstream areas, as they are typically blocking outlets. These dams are sometimes submerged as the pond grows, leaving a consolidated woody debris/beaverlith conglomerate after abandonment.

Figure 10. Typical Check Dam. (Author)

Anabranches

Anabranches were considered to be an stream channel running separately from the main channel for at least 5m, or where a main channel was absent and flow divided into two or more smaller channels. Only channels with active waterflow were considered; ephemeral channels were disregarded for this study.

Figure 11. Meadow with Anabranching Channels. (Author)

Woody Debris Piles

As wood bark is the primary food as well as a component of dams, beaver ponds accumulate large quantities of woody debris. The mass of this material is increased by the trapping action of the ponds, which makes them a sink for materials entering the stream above the dam and depriving the reach below the dam. Wood may be found in the form of discarded food material, with the bark removed, future food material anchored on the bottom of the pond, dam wood, standing or fallen trees killed by inundation, and trapped materials washed into the pond. Due to the variability, woody debris piles were identified as any accumulation of wood covering at least one half of a square meter, and at least two layers deep regardless of diameter. Though this method failed to include much of the woody material, it did identify concentrations throughout the pond area. Active ponds were certainly undercounted, as there was no practical method to survey the entire pond bottom when covered with turbid water. As the method of counting visible piles was applicable to all sites, it did provide consistency across all study sites. In abandoned or drained sites such as M3, examination of the pond area revealed much higher volumes of wood and indicates that substantial woody material is present in most ponds. Of particular interest to this study is the tendency of woody material of all sizes to become embedded in the bottom, through either beaver activity or sedimentation, and thus remain a long-term feature of the later beaver meadow, with implications for affecting later channel development through the meadow.

Figure 12. Woody Debris Piles – One on Bottom Right, one on Bottom Left. (Author)

Canals

Beaver may sometime excavate canals to food sources not yet reached by the pond. Typically, this are approximately 1 m wide and .5 m deep, though this varies. As the pond grows, these become submerged trenches, and the canal may be continued further into dry land. Figure 12 demonstrates a canal heading into an agricultural field, figure C2 shows a canal in a partially inundated area. These canals may have a later influence on the beaver meadow and stream channel formation, and provide a ready path for erosion when a pond is abandoned.

Figure 13. Branched Canal in Agricultural Field. (Author)

Figure 14. Typical Canal. (Author)

Longevity

Longevity was denoted as the total time a dam was in use by beaver, from initial construction to abandonment, washout, or removal. As many dams were in use before the beginning of this study, local informants were used to provide an approximate beginning date for beaver activity in the area. As many sites were on private land, landowners were generally quite familiar with the beaver activity and when it began. On some other sites, such as P2, P3, and P4, personnel and volunteers with the Guilford County Property and Parks Management team were able to provide information for beaver activity. Where possible, beginning dates were verified or at least bracketed by the use of aerial imagery.

Equipment

Standard equipment for measurement included a shortened red and white stadia rod, in 10 cm increments, to provide on-site measurement as well as reference in photographs. For longer distances, a standard 50 meter reel tape measure was used. For areas that were difficult to access, or longer than 50 meters, a Bushnell YardagePro 450 laser rangefinder with a one-yard resolution was employed. For depth measurements the stadia rod was used in shallow areas, while a sounding line was employed from a boat in deeper sections. Initial efforts to use a sonar depthfinder from the boat proved awkward and unreliable, and this method was discarded in favor of manual measurement.

Photographic documentation was via a Cannon SD1300 IS 12.1 megapixel camera, and later augmented by an Apple iPhone5 (discussed below). Locational data was obtained using a DeLorme Earthmate PN-60 handheld GPS unit (also augmented with the Apple iPhone5 as discussed below.)

Many dams exceeded wading depth, and two approaches were taken to obtain depth measurements in these situations. The first, and most portable, was a measuring device fabricated from two lengths of 3/4” PVC schedule 40 pipe, and named the “L-rod.”. This was constructed using an “L” joint to form a large “L” shaped form, with 3 meter legs. Both legs were then marked in .5 meter increments, and a dry erase marker used to add temporary reference measurements depending on the situation. This device was employed by standing on the dam and extending the unit into the pond, dropping the downwards-pointing leg until the bottom was reached. This allowed for depth measurements in deeper water, and as a “feeler” for defining the upstream base of the dam for width measurements. The second method was use of a kayak in situations where it could be transported to the site. This allowed a more thorough exploration of the dam as well as the ability to take accurate depth measurements using a sounding line composed of a brass weight and pre-stretched nylon line, again marked in .5m increments.

An Apple iPhone 5 was used experimentally during later portions of research to compare its effectiveness as a field instrument. It was housed in a Lifeproof® water resistant case, which proved effective to at least .5m. This unit combines a GPS, camera, and note-taking ability in one lightweight package, with the benefit of easily uploading data through cell connections while still in the field. Additionally, the unit provides for geo-tagging of photographs for later reference, so that notes, photographs, and locations can be combined into a single file for future reference. While not replacing the other methods, this unit was accurate and convenient, and results indicate that it is a potentially useful tool for field research.

Where allowed, manual digging equipment (shovels, mattocks, and post-hole diggers) were utilized to sample the dam construction and inspect materials used. Additionally, a remote camera (“game camera”) from Stealth Camera, model Core8, was used at two sites to record beaver activities and construction methods.

CHAPTER V

DATA ANALYSIS AND RESULTS

Data Processing

Table 1 shows all data gathered from all sites. Variables were tested for linear regression using Pearson's r correlation with all other variables. Further testing was performed using linear-log regression; however, no transformation provided improvement in line fit over simple linear regression. Certain variables required modification due to either data type or anthropogenic influences; for example, dams abandoned due to trapping or intentional breaching were not considered for Longevity analysis resulting in n=10, and dam construction types were modified to categorical integer classes (1,2,3); as there were multiple dam types at certain sites, each dam was individually compared to grade(n= 51) to allow comparison.

Pearson's correlation coefficient r was calculated with the Data Analysis ToolPak in Microsoft Excel, which also provided the calculation of coefficient of determination r^2 and p values through linear regression; for this study significance was considered at the α=.05 level.

These correlations, in the form of R values, were placed into a matrix to examine potentially strong correlations (Table 2). Those relationships which also demonstrated a correlation of r^2=> .40 and $p<.01$ were further examined for connections between different correlated variables. Unless otherwise noted, n=15.

Table 1. Variables by Site.

Site	Stream name	Gradient	Impact length m	Watershed Area ha	Construction type	Total Main Dams
M1	Pine Orchard Creek	0.043	250	598	wattle/daub	2
M2a	Beech Creek	0.021	375	6	2 wattle/daub, 1 beaverlith	3
M2b	Beech Creek	0.063	10	1275	sticks/stones	1
M2b	Beech Creek	0.057	23	1275	sticks/stones	1
M3	Camp Creek	0.02	3100	408	7 wattle/daub, 3 beaverlith	10
M4	Conely Branch	0.014	275	349	beaverlith	4
M5	South Prong Lewis Fork	0.011	12	9200	sticks/stones	1
M6	Catawba River	0.049	unknown	2935	sticks/stones	1
M7	Yadkin River	0.028	unknown	7880	unknown	1
P1a	Unamed tributary of Pee Dee River	0.019	541	181	5 wattle/daub, 4 beaverlith	9
P1b	Unamed tributary of Pee Dee River	0.018	625	54	1wattle/daub, 1 beaverlith	2
P2	Unamed tributary of Long Branch	0.022	675	18	beaverlith	5
P3	Long Branch	0.006	1,524	1,130	beaverlith	4
P4	Big Alamance Creek	0.006	1,100	2,260	beaverlith	5
C1	Thompson Swamp	0.001	1,400	2,380	beaverlith	2

Table 1 (cont.)

Site	Stream name	Check dams	Anabranching below dam(s)	Anabranching in meadow	Total Anabranch Channels
M1	Pine Orchard Creek	4	8	3	11
M2a	Beech Creek	7	13	6	19
M2b	Beech Creek	0	0	0	0
M2b	Beech Creek	0	0	0	0
M3	Camp Creek	21	7	29	24
M4	Conely Branch	3	2	5	7
M5	South Prong Lewis Fork	0	0	0	0
M6	Catawba River	1	0	0	0
M7	Yadkin River	0	0	0	0
P1a	Unamed tributary of Pee Dee River	3	7	0	7
P1b	Unamed tributary of Pee Dee River	0	0	0	0
P2	Unamed tributary of Long Branch	6	13	0	13
P3	Long Branch	11	17	0	17
P4	Big Alamance Creek	8	27	0	27
C1	Thompson Swamp	3	5	0	5

Table 1 (cont.)

Site	Stream name	woody debris piles	Dams in type II channel	Dams in type IV channel	Dams in type V channel
M1	Pine Orchard Creek	3			2
M2a	Beech Creek	5			3
M2b	Beech Creek	0		1	
M2b	Beech Creek	1		1	
M3	Camp Creek	19		2	6
M4	Conely Branch	3		1	3
M5	South Prong Lewis Fork	0		1	
M6	Catawba River	0		1	
M7	Yadkin River	0		1	
P1a	Unamed tributary of Pee Dee River	7		5	3
P1b	Unamed tributary of Pee Dee River	3	2		
P2	Unamed tributary of Long Branch	16			5
P3	Long Branch	19			4
P4	Big Alamance Creek	12			5
C1	Thompson Swamp	15	2		

Table 1 (cont.)

Site	Stream name	canals	Longevity (years)	Still active
M1	Pine Orchard Creek	0		no
M2a	Beech Creek	5	11	yes
M2b	Beech Creek	0	0.25	no
M2b	Beech Creek	0	1	no
M3	Camp Creek	3	16	no
M4	Conely Branch	0	7	yes
M5	South Prong Lewis Fork	0	0.17	no
M6	Catawba River	0		no
M7	Yadkin River	0		no
P1a	Unamed tributary of Pee Dee River	7	19	yes
P1b	Unamed tributary of Pee Dee River	3	19	yes
P2	Unamed tributary of Long Branch	2	10	yes
P3	Long Branch	5	14	yes
P4	Big Alamance Creek	1	11	yes
C1	Thompson Swamp	1	5	yes

Table 2. R Correlation Matrix.

	Grade	Length impacted	Construction Type	Main Dams per Site	Check Dams per site	Total Anabranches	Total Woody Debris piles	Total Canals per site	Longevity in years
Grade	1.000								
Length impacted	-0.445	1.000							
Construction	0.654	n/a	1.000						
Main Dams per Site	-0.389	0.670	n/a	1.000					
Check Dams per site	-0.036	0.892	n/a	0.746	1.000				
Total Anabranches	-0.074	0.636	n/a	0.649	0.849	1.000			
Total Woody Debris piles	-0.586	0.843	n/a	0.645	0.795	0.720	1.000		
Total Canals per site	-0.401	0.315	n/a	0.638	0.415	0.411	0.462	1.000	
Longevity in years	-0.406	0.632	-0.322	0.909	0.730	0.671	0.687	0.783	1.000

Results

Longevity and number of main dams of a site demonstrated the strongest relationship, with r^2=.82 (p=.0003.) For this correlation, two sites known to have been affected by anthropogenic removal of dams or beaver were removed, leaving n=10. Longevity was also correlated with Total Number of Canals (r^2=.63, p=.007, n=10). (Figure 15)

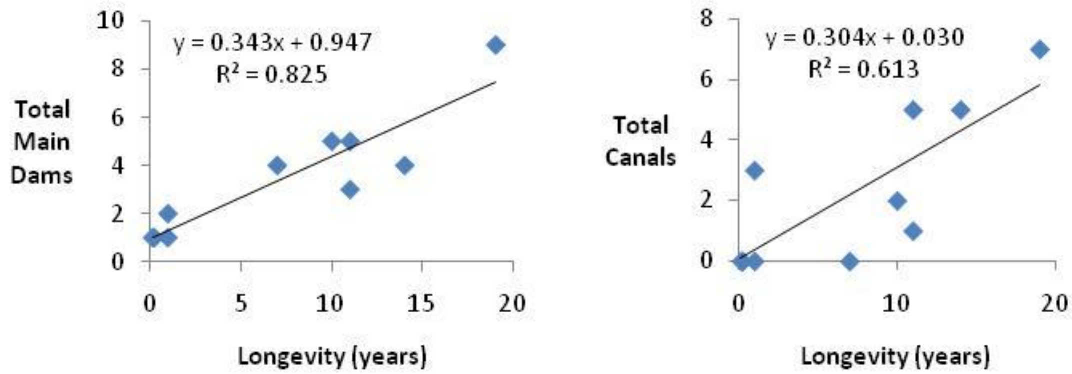

Figure 15. Longevity Correlations.

Total number of Check Dams also showed several relevant correlations. The most robust was to Length Impacted (r^2=.79, p<.0001, n=13), with Total Anabranches second (r^2=.72, p.00006, n=13). Total Check Dams also had strong correlation to the Total Woody Debris Piles (r^2=.63, p=.0004, n=13) and Main Dams (r^2=.55, p=.0014). (figure 16)

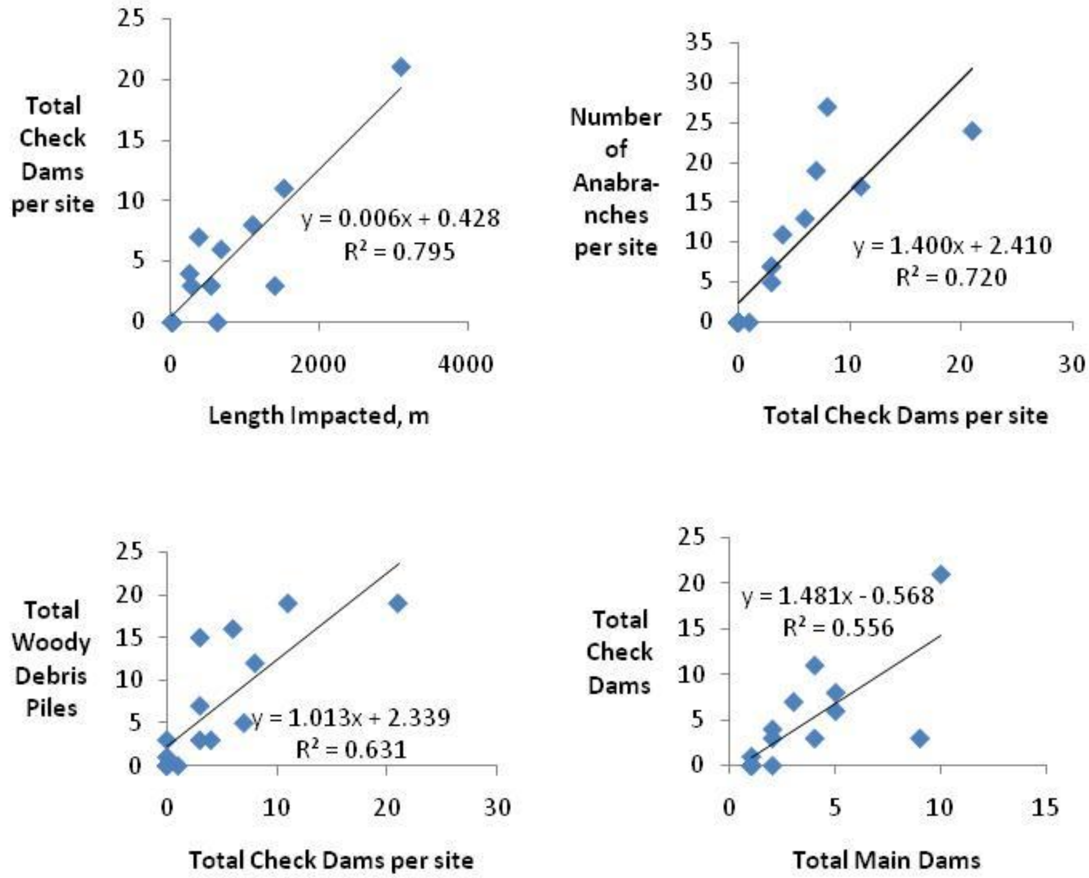

Figure 16. Check Dam Correlations.

As length increases, the potential terrain variation increases, leading to a higher potential need for check dams to contain water and continue expansion. In the sites examined, check dams were not distributed evenly through the total impacted area, but tended to be bunched in areas where local topography provided outlets around the main dam. Due to the channels necessitating check dams, and the porous nature of the dams, the correlation to Anabranching channels to Check Dams fits within the context of physical transformation of the fluvial landscape by beaver activity. The number of main dams also increased the likelihood of Check Dams being needed, as reflected by the level of correlation between these two factors.

Main Dams yielded the most total correlations at the r^2>=.40, however, only two were at the r^2>.50 level. These included the previously mentioned Longevity and Check Dams. Four correlations were noted in the lower range of r^2<.5, r^2>=.40. These were Length (r^2=.44, p<.02), Anabranches (r^2=.42, p=0088), Woody Debris Piles (r^2=.41, p=.009), and Canals (r2=.40, p=.01) (figure 17.)

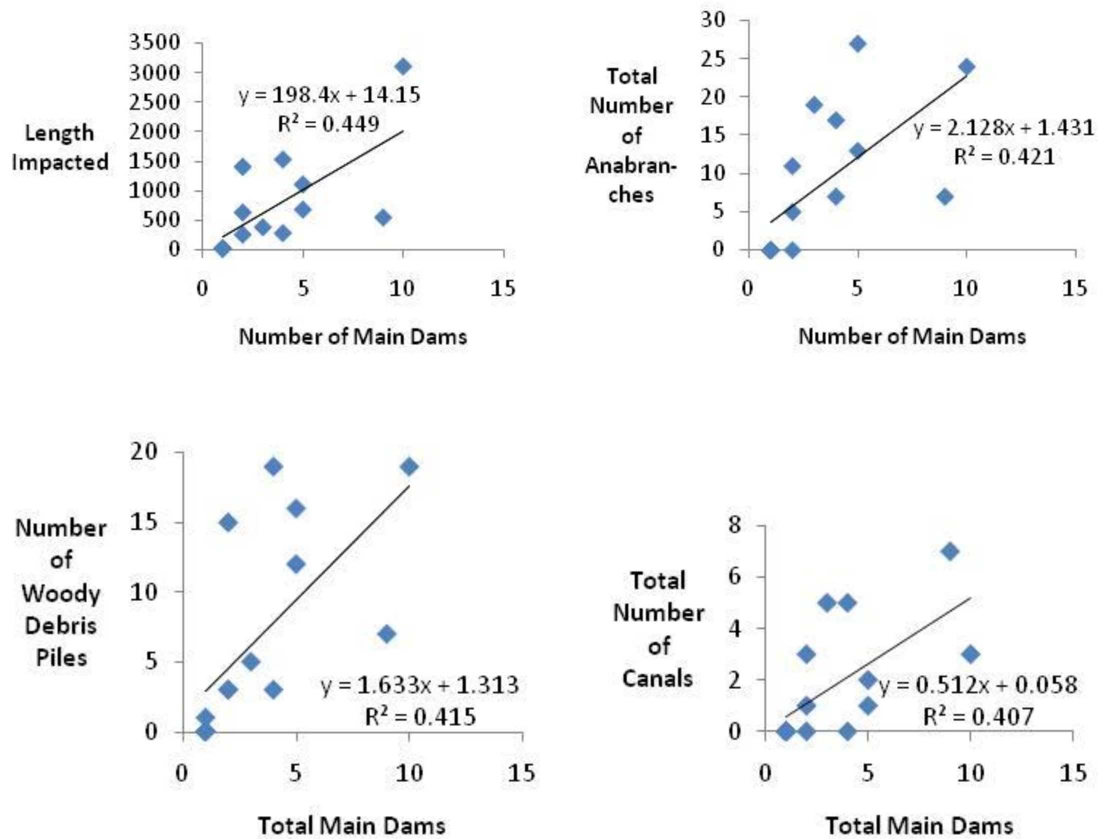

Figure 17. Main Dam Correlations, r^2<.5, r2>=.40.

As Main Dams are the defining feature of beaver ponds, multiple correlations to other factors were expected. However, the low correlations to other factors, with only two over r^2>.50, was unexpected. In view of their position as the foundation structure for the pond and all variables associated with it, the lower r^2 correlations suggest that the creation of the dam creates a cascade of other conditions which drive these other processes; specifically, local conditions such as available materials and topography may exert a strong influence that was not measured in this study.

In addition to the previously mentioned correlations, Total Woody Debris Piles were also correlated with Length Impacted (r^2=.70, p=.0003) and Anabranches (r^2=.51, p=.0024) (figure 18.)

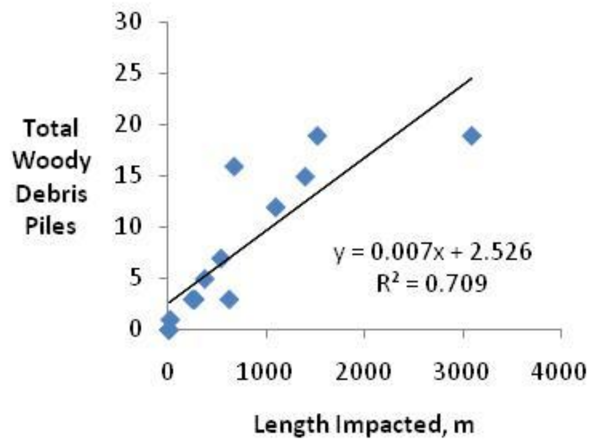

Figure 18. Length Impacted/Total Woody Debris Piles.

The last correlation within the range of considered r^2 values was Grade vs. Construction, with r^2=.43, p= .0000002, n=51 (figure 19.) Based on field observations, this relationship was much weaker than expected, likely due to the overlap in Wattle and Daub and Beaverlith construction at lower grades. Exploration of Construction with Longevity was also explored, but produced very low correlations.

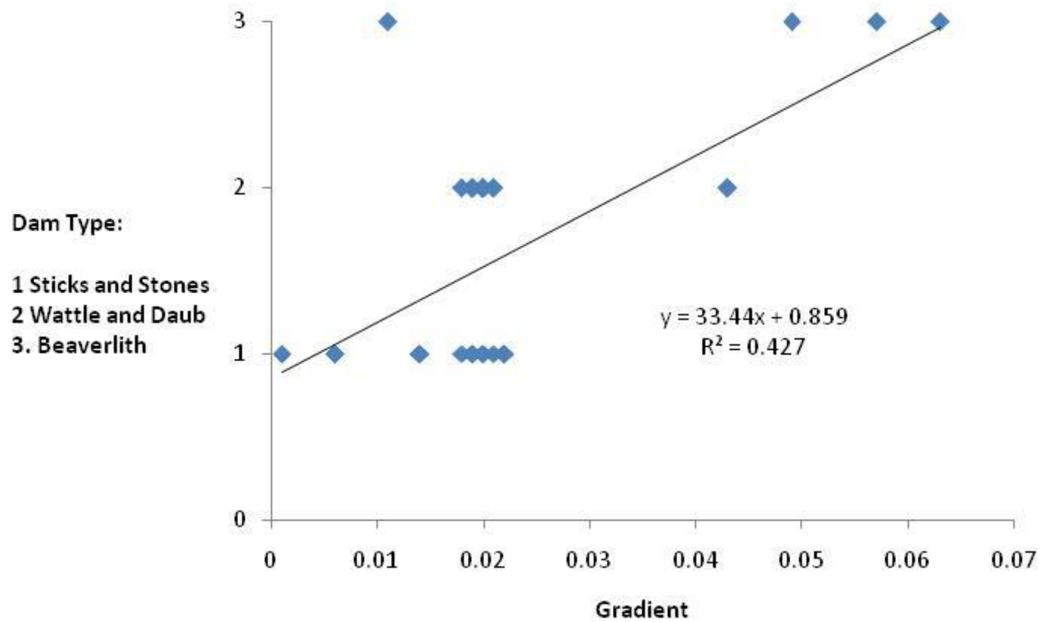

Figure 19. Dam type/Gradient.

CHAPTER VI

DISCUSSION

Variable Correlations

The relationship of Longevity of a site to the number of main dams provides an opportunity and challenge to explore the connections and interactions in a beaver dam site. Longevity encompasses a wide range of factors that influence the success of the dam over time, both physical and biological. The stream flow and channel morphology must be such that the beaver can successfully build a main dam, without high flow events that remove the dam. Biological factors include (but are not limited to) sufficient food and woody construction resources, and survival of the beaver (including accidental and predation losses). At the nexus of abiotic and biotic factors is a physical landscape that allows rapid enough expansion of the pond area to reach additional food resources. Canals are a part of this expansion, increasing the harvesting area beyond the main pond area. They may be considered as a mechanism to support the site by reaching resources to continue the expansion; a sort of colonialism on a local scale.

This connection to the number of Main Dams continues with the relationship between main Dams and Check Dams. Any given dam may be situated such that a check dam, or dams, may be needed to confine water to the pond area and continue to expand the total pond area, meeting the beavers' need to access new food sources. As the number of main dams increase, so does the potential need for Check Dams. Check dams are also related to Length Impacted, the relationship between Main Dams and Length impacted is not unexpected; however, it is much lower than either Main Dam to Check Dams or Check Dams to Length. This lower relationship may be due to the variable length of impact; some reaches had multiple dams in a short distance, while others had few, or just one, over longer distances. Again, local topography appears to play a role, as does the action of beaver in choosing specific sites within a series of dams to create a new dam. In this regard, vegetation may play a role through food and dam material availability.

The relationship of Check dams to Woody Debris Piles was particularly evident in sites such as M3, Camp Creek, which was abandoned during the study, providing the opportunity to examine the new meadow areas during the process of draining, and physical exploration of the former pond bottom. The locations of the woody piles visible during the active stage changed little, but as water levels lowered, more piles were noted, and as water began to form distinct channels, several new piles developed against obstructions. Many of these piles were then left on dry areas as the water receded further, an indirect result of beaver activity. Based on observations at this site, it is likely that Woody Debris Piles at other, active, sites were undercounted, and that the piles are not static during the abandonment phase. Rather, they are still mobile as the water level drops and consolidates material in the former pond, and that obstructions (stumps, LWD, and former beaver lodges) may continue to aggregate woody materials during high flows after abandonment.

The correlation of both Check Dams and Woody Debris Piles to Anabranching channels both below the Main Dam and in meadows between active dams and abandoned sites provides a connection point for the above-discussed correlations. As shown in figure 20, these variables form a tree of connections amongst the most strongly-correlated variables in a beaver dam system.

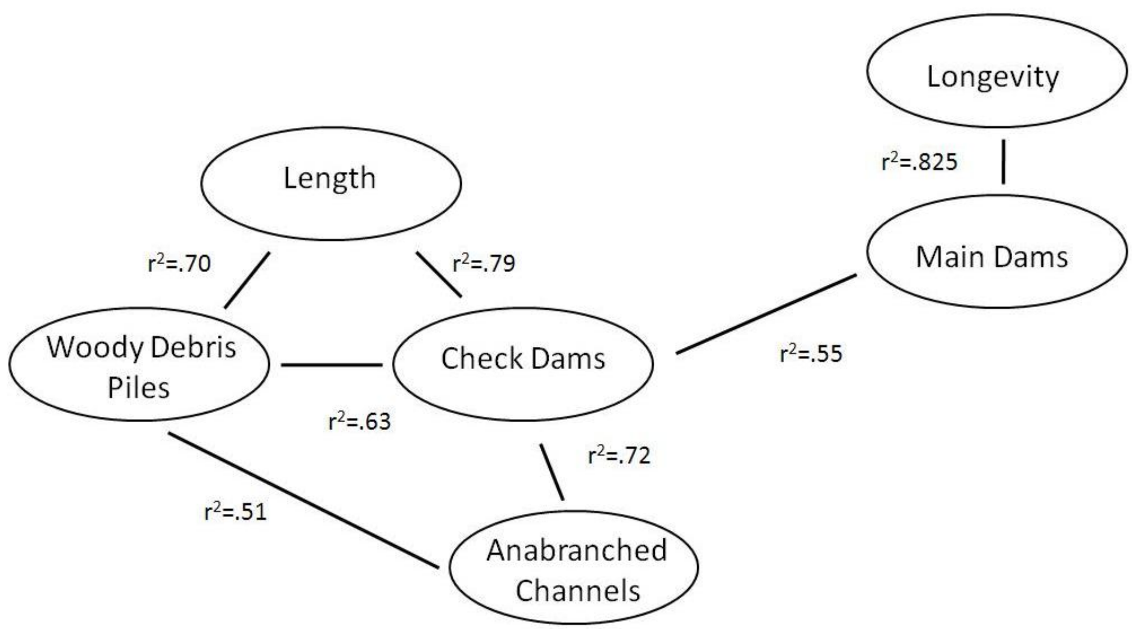

Figure 20. Connections Between the most Strongly Related Variables in Beaver Systems.

Dams

The “classic” beaver dam in the public imagination is a woody structure in an idyllic setting, surrounded by large pond of cool, clear water. While this certainly does exist, the beaver dams more likely to be encountered in North Carolina will be in less than pristine settings; the habitat affected by three centuries of post- European contact agriculture and land use practices. Wood may be present as a covering, but many dams are primarily of beaverlithic construction, more akin to a southwestern adobe lodge than a log cabin. The styles of construction found during this study had some relationship to grade, but it is unclear that grade directly influenced the construction. More likely, variables not studied in this project, especially sediment storage, influenced the materials available for construction. High gradient mountain streams in confined channels have little sediment available for beaver use; rocks and wood are readily available in most of these settings, while lower gradient streams may provide more access to sediment. The change in composition, from sticks and stones to wattle and daub to beaverlith, generally signals a transition to longer-lasting ponds of beaverlith construction, though the correlation was weaker than expected. However, this correlation indicates some connection, with a general trend in construction types based on grade and region.

Another indication of the importance of dams in forming a basis for other features to develop is the steepness of the relationship between Main Dams and several other variables (figure 17), including Check Dams (y=1.481x-.568), Main Dams to Length (y=198.4=1.931) and Main Dams to Anabranches (y=2.128x+1.931). These sensitivities suggest that while some of the correlations are weaker than between variables at the sites, the number of Main Dams Main at a site plays an important role in the develop of these other features. Related to the role of Main Dams, the correlations between Check Dams and Total Anabranches not only has an r^2=.720, the slope of y=1.4008+2.410 (figure 16) also indicates a higher sensitivity than most other correlations examined. As the purpose of both Main Dams and Check Dams is to alter the course of water, impounding it with subsequent energy loss, and both act to trap sediment and have multiple outlets, these physical process may be key to the actual development of other variables, especially anabranches.

Channels

Beyond stream grade, the channel form, on a very local scale, is important to the formation of dams and ponds, through both physical and biological factors. In incised streams, access to vegetation for food and building material is more difficult, and dam height must reach the top of the incised area before flooding spreads and provides aquatic access to resources. In the case of deep, narrow incisions, the time involved in building a dam tall enough to reach the floodplain may deplete both food and construction materials before new resources are inundated. Pollock et al (2014) discuss using beaver dams or analogues for incised stream restoration, but that proposal is applied to incised channels large enough to develop meanders within the incision. In a typical first or second order incised stream (CEM Type II) in the piedmont of North Carolina, the channel is too narrow for development of normal stream features – a 2 meter width leaves little room for stream development, and beaver are focused on food rather than restoration. Site P1a did have a series of 5 dams in an incised channel, creating a series of still pools backed up to the next higher dam, and fresh signs of activity were noted throughout this reach; however, none of these ponds had reached the floodplain, and all remained relatively static in size over 4 years of observation. Only one lodge was observed, a bank lodge in the 4 pool downstream, near the main pond. The purpose of these dams is unclear, as they provide no additional food access, only a protective area and transit corridor upstream. They may represent expansion of the main pond population, with young beavers utilizing sub-prime areas.

Site P1b contained the most unusual dam found during the study: a 4m tall dam spanning a narrow incised channel, 2.5m at the bottom and 7m wide at the top, with a total dam length across the channel of 10.5m. The top of the dam was 1.5m wide, the base approximately 13m, though measurement of the submerged portion was difficult and not deemed highly accurate. Water depth was 2.5m at the deepest spot found. This dam had survived at least one large flow event which submerged the adjacent farm field to a depth of 4 feet according to the landowner, indicating that the actual dam was likely 2-3m underwater during this event. Investigation by probe indicated that the dam was likely at the upstream end of the incised channel, and initial flooding likely provided enough resource access to continue the construction. Given the dam's size and beaverlith construction, with its history of durability, it seems likely that this structure will continue to be a part of the landscape for many years, even if abandoned.

Channels that are confined, though not so tightly as to be considered incised (CEM Type IV), and a new floodplain is being created between the high walls of the former incised channel, offer increased suitability for beaver activity. Physically, a connection to a wide floodplain means direct access to wood and soil resources, the area flooded increases considerably with only small height increases of the dam, and high stream flows have increased area for energy dissipation and attenuation, contributing to the survival of the dam. Increased area also provides multiple sites out of high flow areas for lodge construction. Biologically, these riparian zones may contain both herbaceous and woody material in abundance, fueling beaver activity. These areas are identified not purely through gradient, but rely on the microtopography of the stream channel to provide adequate area for the above traits to occur. Site M3 provided an opportunity to observe the difference in varying floodplain width over a long reach; very different forms evolved in different areas as a response to the very local conditions. The upper reach had very well connected stream floodplains, and developed into a complex of multiple dams, check dams, and anabranching channels. However, at the downstream end of the upper reach, the valley narrowed, confining the stream through a large patch of rhododendron (*Rhododendron sp.*). A dam was built in this reach, primarily of rhododendron, but the pond covered only a small area. Once the available food trees were cut or stripped of bark, activity fell, and although the dam continued to be maintained no further expansion was observed. At the downstream end of the lower reach, beaver activity ceased as the stream entered a narrow valley filled with rhododendron. Though vegetation may have played a role (discussed below), the confined channel and narrow floodplain offered a poor location to meet needs and build a large pond with expansion area.

All of the failed dam sites were in confined channels with little sediment or soil materials available at the waterline. These sites forced beaver to rely instead on woody material dragged down into the channel, and sand-to-cobble sized materials from the streambed. As noted earlier, beaver are well-equipped to cut and drag woody materials across dry land into channels; however, they are poorly equipped to move dry soils. Bank lodges and bank mining offer sources of earth, but may be limited depending on the specific site. Both of these activities may also have a later impact on the channel by moving otherwise stable materials into the water, and by leaving undermined bank areas prone to future collapse. The feature found to be most interesting in these sites was the shelf of coarse materials, up to cobble size, remaining in the channel after the woody/herbaceous materials and soil have been mobilized downstream (figure

21). I have not found this phenomenon described in previous literature, and believe that it relies on a combination of beaver activity, substrate, and flow conditions to materialize. Though beaver certainly can and do move large stones (figure 22), the solid layer suggest that the dam acts in an accumulative manner as a trap, collecting the coarse materials at the upstream base during high flow events.

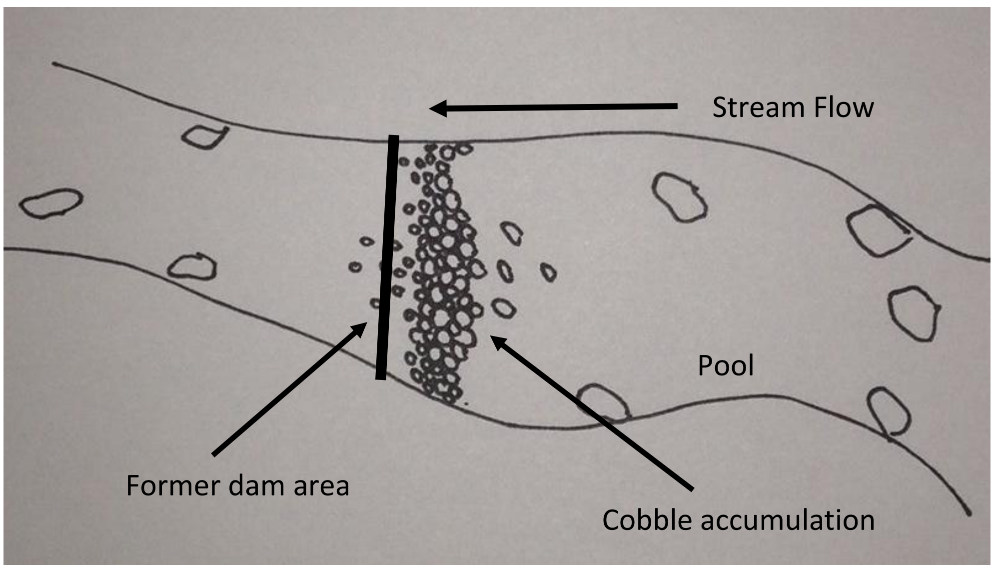

Figure 21. Cobble Layer as a Result of a Sticks and Stones Dam. (Author)

Figure 22. Stone Moved into Dam by Beaver; approximately 19cm x 15cm x 14cm. (Author)

Most of these aggregations were dispersed within 3 months, though some persisted at least 9 months. Their effect on the channels is unknown, but the armoring of the bottom along with a decrease in depth at their location in the channel suggest several possibilities for impact on channel behavior locally and downstream.

Channels that are well connected to their floodplain (CEM Type V) offer wider floodplains for expansion, and from beaver prospective, ideal living conditions. Material, including woody, herbaceous, and earthen, is readily available at the stream edge. Food is also nearby, and small increases in dam height offer large gains in territory flooded. Canals are readily excavated in such instances, and offer a quick expansion to favorite food sources not yet flooded. Beaverlith construction dominates both dam and lodge building, creating durable, erosion-resistant structures that may remain for years if not decades beyond abandonment. Here, the ponds began to take on ages of 19+ years, with anecdotal stories of dams persisting for over thirty years (Neuman, pers. comm., 2013.)

Heterogeneity of Ponds

In these long-lived dams, heterogeneity increases as sediment accumulations can become quite substantial as discussed by Butler and Melanson (2005). This sediment, along with organic material, provides a rich substrate for future terrestrial plant growth when the pond is finally abandoned, and also an easily reworked material for channel development as the pond level drops and the stream begins a find a path through the former pond floor. Confounding a straightforward assessment of new channel behavior, however, is the above-mentioned vegetation which can grow within a few weeks to months depending on the time of year, and the large amounts of woody debris left in and on the sediment. Observations during this project noted woody debris in both active and abandoned ponds at lower gradients where large pools had persisted over several years. These consisted of classic stream LWD, washed into the pond from upstream; beaver food discards, both singly and in piles, and large trees felled by beaver or killed by inundation of the roots. In several instances many trees killed by the flooding continued to stand, providing both a source of LWD for several years, and visually indicating the presence of rootwads and stumps in the pond floor. While woody materials generated directly from beaver activity (including standing/fallen deadwood) were randomly located through the ponds, LWD from upstream typically followed a pattern of settling in or near the primary inlet path to the pond, and in multiple dam sequences, most was contained in the uppermost pond.

This distribution creates a condition where, upon draining of the pond, LWD as well as coarser materials are concentrated in the former main channel, and may influence the creation of anabranches in this area as the stream creates routes through the obstruction. These channels may rejoin below the erosion-resistant obstruction and flow back into the former main channel, or may be diverted further through the soft sediment and multiple instances of beaver discard piles, random LWD embedded in the sediment, fallen trees, stumps, lodges, canals, and quick-growing vegetative cover. The inclusion of all of these factors illustrates that the pond and resultant meadow is far more than a simple sediment sink; it is a rich, heterogeneous accumulation of biotic and abiotic factors, some easily eroded and some erosion resistant.

Lower ponds in the sequence may develop this condition before the upstream dams deprive them of non-beaver LWD and coarse sediments, or may lack this feature if created later than the upstream dams. However, they will still contain the beaver-generated woody materials, and have the additional influence of multiple water outlets from the upstream dam, creating a forced anabranching; these channels in turn are influenced by the various features noted above. In sites M3, M4, P1, P2, and P3, this was indeed the case as anabranching associated with both abandoned ponds (figure 23) as well as downstream of, or between, active dams such as site P3 (figures 24, 25) was documented.

Figure 23. Anabranches in Abandoned Pond Area, Site M3. (Google Earth)

Figure 24. Anabranching at Site P3. (Author)

Figure 25. Aerial view of Site P3; Same Area as Figure 25. (Google Earth)

These observations support Walter and Merrits (2008), Hartranft et al (2011), and Elliot et al (2013) in the view of pre-European contact steams as composed of multiple channels in a meadow environment, rather than the more familiar single channel streams currently observed. Walter and Merrits first proposed this idea as a result of work with mill dams and the fluvial morphology generated by them, as field studies indicated that buried streambeds contained more pond-like sedimentation than stream sedimentation; however, no mechanism was provided to explain this condition, nor did Elliot et al (2013) provide a basis for this proposed condition in their survey of vegetation form early 1800s sediment layers. Hartranft et al (2011) describe restoration of an incised stream to create an "anastomosing channel valley bottom floodplain system (ACFS)," a condition they trace back to pre-European impact, but do not explain the origin of this form. In this study, I provide support for their observations in the form of direct biological influence by a keystone species. This, in turn, is supported by Butler and Melanson (2005) and the estimate of 60-400 million beaver in North America pre-European contact. Given the stream impact generated by 10 years of beaver activity in low-gradient areas, the impact of 60 million beaver over several thousand years can account for the establishment of a stable stream form, as beaver meadows are continuously reworked as sufficient new woody growth is established. The "reworked" aspect of this statement is important in considering the actual state of stream channels – were the number indicated by Butler and Melanson continuously active at stationary sites, only larger streams could have been free-flowing to any extent. However, unlike many physical factors which operate continuously over time, beaver activity is regulated by resource availability. Once a pond reaches a threshold where dambuilding no longer yields enough pond expansion to access new food resources, it is abandoned in favor of more abundant resources. While fast-growing species such as the Willows (*Salix*. sp.) and Alder (*Alnus* sp.) may provide some resupply in inundated areas, Terwilliger and Pastor (1999) note that regrowth of larger woody species may be delayed for many years due to soil conditions created by inundation. Given this cycling of dam building, abandonment, and regrowth, we see the beaver impact on streams as a dynamic rather than static situation, where stream segments may undergo multi-year periods of alternating impoundment and free-flowing. The evolution of beaver dam meadows, in particular the channel evolution that may occur following abandonment, needs further study as a channel evolution model specific to beaver meadows could have application in understanding both physical and biological functions of these sites.

The connection between beaver ponds and anabranched stream segments is likely not unknown. Trappers, wildlife biologists, and others that frequent beaver-inhabited areas and observe habitat changes over time are probably familiar with the changes produced by beaver activity; however, their primary concerns have been other than stream morphology, and these changes considered to be obvious based on multiple observations and familiarity.

However, information gathered in this study provides a measure of quantitative evidence to connect beaver impact to changes in fluvial systems, especially in reference to the suggestion that pre-European impact streams had a form very different from current forms.

Restoration

The last area of consideration is the use of beaver for restoration. Pollock et al (2014) propose the use of Beaver dams or analogous structures to restore incised streams, but consider only streams wide enough to develop a typical meandering stream form that would eventually accumulate enough sediment to raise the channel back enough to reconnect with the former floodplain. Their description refers to the pond/former pond area as complex, but rely on artificial beaver dams (Beaver Dam Analogs) to create this situation. Hartranft et al (2011) describe restoration of a stream to a boggy, multi-channel meadow condition nearly identical to an abandoned beaver meadow in the piedmont of North Carolina (site M3 in this study.) Both focus on restoration, though Pollock et al (2014) use the sediment trapping effect of the dams to accumulate enough material to build a meandering stream that over time might fill the incised channel while retaining the meandering form until reconnection with the floodplain is established, and Hartranft et al (2011) describe a heavily engineered replication of a proposed pre-European settlement form. At the intersection of these two studies is the beaver – recognized by one for the ability to trap sediments, and emulated by engineering in the other, and here the question of whether or not beaver might provide a useful tool in both scenarios materializes. While sedimentation and accumulation of LWD as described by Pollock et al (2014) is a major component, I suggest that the complexity described in their proposal goes beyond accumulation to the multiple effects of actual beaver activity. Instead of accumulation of sediment and woody materials by physical processes, the cutting and movement of woody materials into the pond, aggregated food and discard piles of woody material, active mobilization of sediments into dams, and continued expansion activities creates the more complex, heterogeneous, situation that results in anabranching channels.

Based on the results of this project, beaver can certainly restore streams to the pre-settlement condition theorized by Walter and Merrits (2008), Merrits et al (2001), and Elliot et al (2011), through the mechanism proposed by Pollock et al (2014). Concerning sedimentation, the observations of this study and the ability of beaver to burrow and excavate soils, moving them into the stream channel, indicate the possibility that beaver may have been responsible for some of the sediment mobilization prior to European influences. Regardless of the source of sediment, beaver dams are capable of trapping and at least temporarily storing it within the stream system. Most modern stream restoration projects actually create conditions favorable to beaver colonization, with resultant problems occurring when beaver do colonize projects and disrupt the planned restoration by destroying riparian planting and submerging control structures

(Curran, pers comm., 2009.) It is somewhat ironic that restoration projects are impaired by a keystone species capable of restoring the same stream, though in a very different manner – biological processes instead of hard engineering – and suggests that beaver might prove a valuable tool in restoration.

There are, however, considerations in this approach. First, beaver restoration may be somewhat unpredictable on a local scale as far as time and final outcome, as well as the threat of movement to undesirable locations to practice their restoration. Second, the boggy meadow result is in contrast to the flowing, single-channel stream that most residents of North America are conditioned to accept as a “wild” stream, and might limit recreational activities on some stream reaches. These two considerations are primarily of perception; beaver in fact offer a potential tool for restoration of certain stream reaches, and offer the added advantage of producing a habitat favorable to many species not available elsewhere in the modern landscape. This last returns us to the concept of rewilding; restoring not only pieces of lost landscapes but entire ecosystems. Beaver ponds constitute a rewilding scenario in miniature: over a period of years animals and plants that rely on the pond/wetland conditions created by beaver dams can return to these ecological islands. As a practical consideration, streams can be (and typically are) restored one reach at a time; rewilding projects typically require a much larger area to support the proposed ecosystem. Beaver offer a niche between the two, reworking long reaches over time, and creating a stream-linked ecosystem with attributes not typically found in the modern landscape.

As with all rewilding efforts, concerns exist over the migration of animals (beaver) out of the ecosystem with potential negative impacts to anthropogenic interests; however, beaver are confined to stream areas, and likely much easier to contain than bison, elephants, or cheetahs. Bronaugh (2010) describes the relationship between lost megafauna and certain trees in the North American landscape; given the large number of evolutionary ancestors of the modern beaver, it is quite possible that there remain connections between beaver and other plant or animal species that are currently unknown. One clue that points in this direction is the ability of many North American hardwoods to resprout from a trunk; an attribute missing from most South American trees; South American trees evolved without beaver or other tree-felling analogs. Thus, beaver are excellent candidates for restoration and rewilding projects, though concerns about perception and unintentional consequences would need to be addressed before any formal application.

Depletion of Food Resources

One aspect of beaver behavior and dambuilding not addressed in the original study questions was noted through the observations over many types of sites and settings. As mentioned above, beaver may attempt dambuilding wherever they have available food resources to support that endeavor, whether successful or not. The observation of the abandoned dam site at the upstream portion of site P3 suggested that after the dam failed, beaver did not attempt resettlement of the site. The lack of small, <15 cm trees and underbrush suggests that the lack of food and foundation materials may have rendered the site unusable for several years; those resources were expended in the original dambuilding attempt, and without them the site is unsuitable for use until they regrow. If this observation is correct, it would suggest an option for beaver control in certain situations where the food and foundation base could be removed on a long term basis. This could be effected by mechanical removal of trees and shrubs, followed by herbicide spraying to maintain a strictly herbaceous landcover; controlled burns (as now practiced to reintroduce Carolina Savanna), or vegetation removal and replanting with plants not attractive to beaver. As noted at site M3, beaver used rhododendron (*Rhododendron sp.)* to construct a dam to reach food materials, but did not consume the rhododendron itself. Coniferous trees generally were untouched by beaver (though one instance of cutting several pines was noted, no bark was removed), and no species of *Juniperus* were observed to have been cut at any location, either at the study sites or elsewhere. Thus, clearing and replanting with none-food trees, while removing other species, could be a potential strategy at some locations to control damming without resort to trapping and removal. While the sites where this might be employed are limited, it would offer a long-term solution rather than the dam-trap-breach-dam cycle many locations are currently experiencing. In a rewilding situation, controlled burns would foster the growth of native grasses and forbs (and the species reliant on them) while preventing woody plants; providing specialized wildlife habitat while dissuading beaver from that area. This approach would provide a “soft” approach to beaver control that might prove more palatable to portions of the general public than trapping, and thus might draw support (public, political, and financial) to protect suitable areas.

CHAPTER VII

CONCLUSIONS

Research Questions

This study posed four questions in the introduction:

1. What is the physical morphology of beaver dams in North Carolina?

2. Does beaver dam morphology differ between the Mountain and Piedmont physiographic provinces of North Carolina?

3. Can beaver activity explain some aspects of the hypothesized anastomosing pre-European wetland streams described by some researchers?

4. Are there any effects of beaver activity that might be useful in stream rehabilitation/restoration projects in North Carolina?

Based on research and observation, these questions can be answered, and those answers supported as follows.

1. What is the physical morphology of beaver dams in North Carolina?

Beaver dams represent a combination of available materials, and vary considerably depending on local resources. Three general types of dam construction were identified: Sticks and Stones, Wattle and Daub, and Beaverlith. Woody material is found in all types, though it is used in conjunction with stone, herbaceous materials, and soil, depending on availability. The most noticeable difference was found between beaverlith and the other two types; both the Sticks and Stones and Wattle and Daub utilize wood as the primary framework for the dam, which is then filled with other materials, while Beaverlith uses a soil/herbaceous material mixture to create a nearly homogenous main structure, analogous to a mud/straw adobe, with woody material covering the downstream face. Experiments with the beaverlith dam indicated that it is resilient to breaching damage due to the herbaceous material, and beaver are capable of quickly repairing it. Photographic evidence (figures 6-9) show beaver intentionally including grasses or sedges in the repair work, and not as accidental inclusions while moving soil to the area.

Based on this study, beaver dams in North Carolina will likely be one of these three types, with some dams representing transitional forms with features from other types as dictated by local conditions.

2. Does beaver dam morphology differ between the Mountain and Piedmont physiographic provinces of North Carolina?

Dam construction is tied to available resources, and these resources generally vary by province due to the physical landscape. Lack of soil materials in the Mountain Province dictates dams based on other, available, materials, leading to construction of both sticks and stones dams and wattle and daub dams. As the landscape changes in the Piedmont Province to favor more soil availability, wattle and daub dams persist to some extent, but beaverlith dams become widespread. However, local resources may dictate the construction of wattle and daub dams in low gradient areas, and these types may be mixed in a single site, demonstrating the beaver are not necessarily predisposed to a given construction style. The Type is correlated with Grade, but only at the r^2=.427 level, indicating that, even with the sharp break in grade between the Mountain and Piedmont Provinces, the type is not solidly linked to grade or Province. However, a general trend was noted, with Sticks and Stones found only in the steeper grades while Wattle and Daub was noted at slightly less steep grades, and continued into low gradient areas after Beaverlith had become common. This overlap between the last two Types precludes a solid prediction of single dam type based solely on grade or Province, even though the general trend gives some indications of the expected range of Types.

Investigation of Coastal Plain Province dams might help refine prediction of dam types, however, these ponds are typically much larger than either the Mountain or Piedmont Province dams, and much more difficult to study in fine detail. Site C1 demonstrated the need for both more time and equipment resources to gather data at the same resolution as the other sites, and no further sampling was attempted in the Coastal Plain Province.

3. Can beaver activity explain some aspects of the hypothesized anastomosing pre-European wetland streams described by some researchers?

Observations from this study indicate that beaver, given enough time, do create stream reaches that closely resemble the pre-European contact forms described by some studies. In particular, the beaver create meadows with multiple channels due to both multiple dam outlets and the formation of rich, heterogeneous meadows with accumulated sediments, stream LWD, beaver related woody debris and discard piles, check dams, and the dam itself, with the residence time playing an important role in the development of these features. The complex accumulation on the pond floor provides an excellent substrate for quick, dense vegetative growth upon abandonment, and this likely aids in the stabilization of the multiple channels that evolve in the early abandonment stage. Beaver activity may provide a biological mechanism for the production of the hypothesized multi-channel meadows pre-dating European settlement.

4. Are there any effects of beaver activity that might be useful in stream rehabilitation/restoration projects in North Carolina?

Beaver activity is a natural process that maintains a given set of conditions over time when undisturbed; thus new beaver activity is restoration. However, issues with control and public perception limit the usefulness of beaver for restoration in North Carolina. Beaver structures, or their analogs, do present an option in some restoration projects – the use of beaverlith materials instead of stone in some traditional restoration projects, and the use of buried/ensconced woody debris, beaverlith lodge analogs, and disrupted terrain emulating canals in wetland or multi-channel restoration to maintain anabranched form while allowing the stream to maintain some degree of dynamic adjustment ability. When moving from restoration to rewilding, beaver, as a readily available keystone species, offer a powerful tool to create new habitat types that support a variety of otherwise displaced species and form the nucleus for introduction of other species, both plant and animal, that may benefit or rely on the patch disturbance effect of beavers.

Future Research

Several observations during this project pose question for future study. The observation of cobble material left in several Sticks and Stones sites after the dam had been washed out suggests that this accumulation of material may not be uncommon in some situations. If so, it may play a role in channel morphology that has been heretofore unrecognized as a beaver impact by creating an armored stream bottom, and possible a slug of this heavier material as it is displaced downstream. Questions relating to this study might be determining the frequency of these deposits, longevity, and effect on channel form.

Another question raised, especially in light of Pollock et al (2014) and the use of Beaver Dam Analogs, is the early recovery stages of former millpond sites in relation to the effects of beaver dams. Both serve to trap sediment and LWD as a path to creating anabranched streams – does the record of dam removal and subsequent stream recovery support the use of BDAs as a means of stream restoration, or does the process of creating an anabranched system require a more complex environment?

Concerning CEM models, do beaver speed the process of moving through different types of channel configuration, and if so, by how much compared to non beaver impacted streams in the same area?

Related to CEMs, what is the evolutionary path of channels in abandoned beaver ponds? Do they follow Shumm et al's 1984 model, or does the heterogeneity of the site influence a different evolution? In addition, what is the timescale of channel evolution in abandoned ponds, and how does the cycle of beaver colonization, abandonment, and recolonization interact with this physical process?

Finally, based on beaver requirements, is food and material deprivation through cutting and replanting with non-woody or unpalatable plants a viable method of discouraging beaver use in certain areas, and if so, is this a cost-effective and publically acceptable method of controlling beaver activity in critical areas such as culverts, railroads, bridges, and the like?

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APPENDIX A

SITE DESCRIPTIONS

Site M1, Pine Orchard Creek. Watauga County, NC

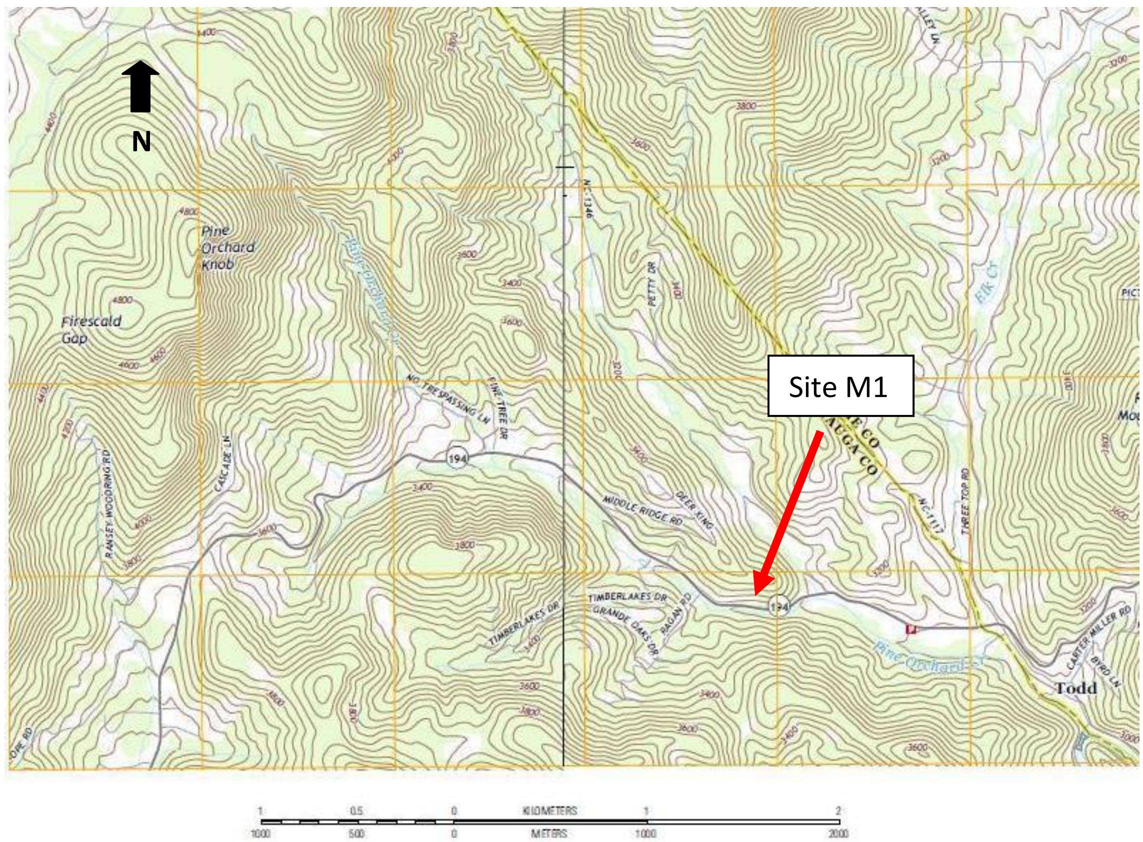

Figure A1. M1, Pine Orchard Creek, NC. (USGS Topo)

Pine orchard Creek is a second order stream in the northeastern corner of Watauga County, NC. The area of the stream utilized by beaver is characterized by steep terrain on the mountain sides (the primary headwater stream has a grade of 22) before reaching the main stream valley, though the valley floor is both lower-gradient and up to 50 meters wide. This dam was constructed in approximately 2005 and lasted until 2012 when the beaver population was removed. During this active period the main downstream dam reached a maximum of 32 meters in length, a maximum width of 4 meters, and a maximum height of 2 meters. The beaver complex consisted of two main channel dams, with several smaller check dams on the pond edges, and one smaller main channel dam in the uppermost area of the complex. The three main channel dams were all in existence by 2008, though the upper dam was abandoned in 2010. Smaller check dams were variable in number as pond level increased, submerging some while requiring new construction to close gaps. In total, 4 check dams were recorded during the study period 2008-2012. A total of 250 meters of stream were affected by beaver activity at this study sight, with a total area of approximately 10,000 m2 inundated.

Observations over the 4 year study period indicated a dynamic system of stream outlets emanating from the three main channel dams, with the most downstream dam evincing the most dramatic changes as the stream left the confines of the dammed area and formed multiple channels over a 30 meter distance before finally rejoining into a single channel.

Figure A2. Pine Orchard Creek site, Downstream of the Downstream Dam during a High Stream Flow. The High Flow Illustrates the many Small Channels that have been created by Dam Leakage over a 5 year period. (March, 2010) (Author)

As figure A2 Illustrates, the downstream dam has created a network of stream channels through the valley floor. Approximately half of these channels carry some amount of water during normal flow, with the others picking up water as flow increases through and over the dam. Of note in this situation is the formation of these channels, active or not, which may influence future stream behavior through either geomorphological activity or biological activity.

After beaver activity ceased, the dams developed leaks in multiple areas over a two year span, with the stream forming a coherent main channel in 2014.

However, as figure PO3 shows, multiple side branches continue to exist, with at least three carrying water at all times and 5 more carrying water during high flow events.

Figure A3. 2014 Aerial Photograph of the Former Beaver Dam Site on Pine Orchard Creek, Showing the Remnant Beaver Meadow and Remaining Secondary Branches. (Google maps, 2014.)

All of the dams in this complex were of wattle and daub construction, with woody materials forming a matted lattice filled with earthen materials, and limited rocky material of 10-30 cm long dimension interspersed. Limited herbaceous material was present in the dam construction. As of 2015, nearly all of the dams still have recognizable remains colonized by herbaceous plants; all three main channel dams have large (2m+) breaches while the smaller wing dams are largely intact though nearly buried in sediment and vegetation. Approximately 50% of the original inundated area remains waterlogged, with small channels carrying water during high flow events. No large woody plants have colonized the area, though the herbaceous materials have created a thick carpet of vegetative material over the area.

Site M2, Beech Creek, Watauga County, NC

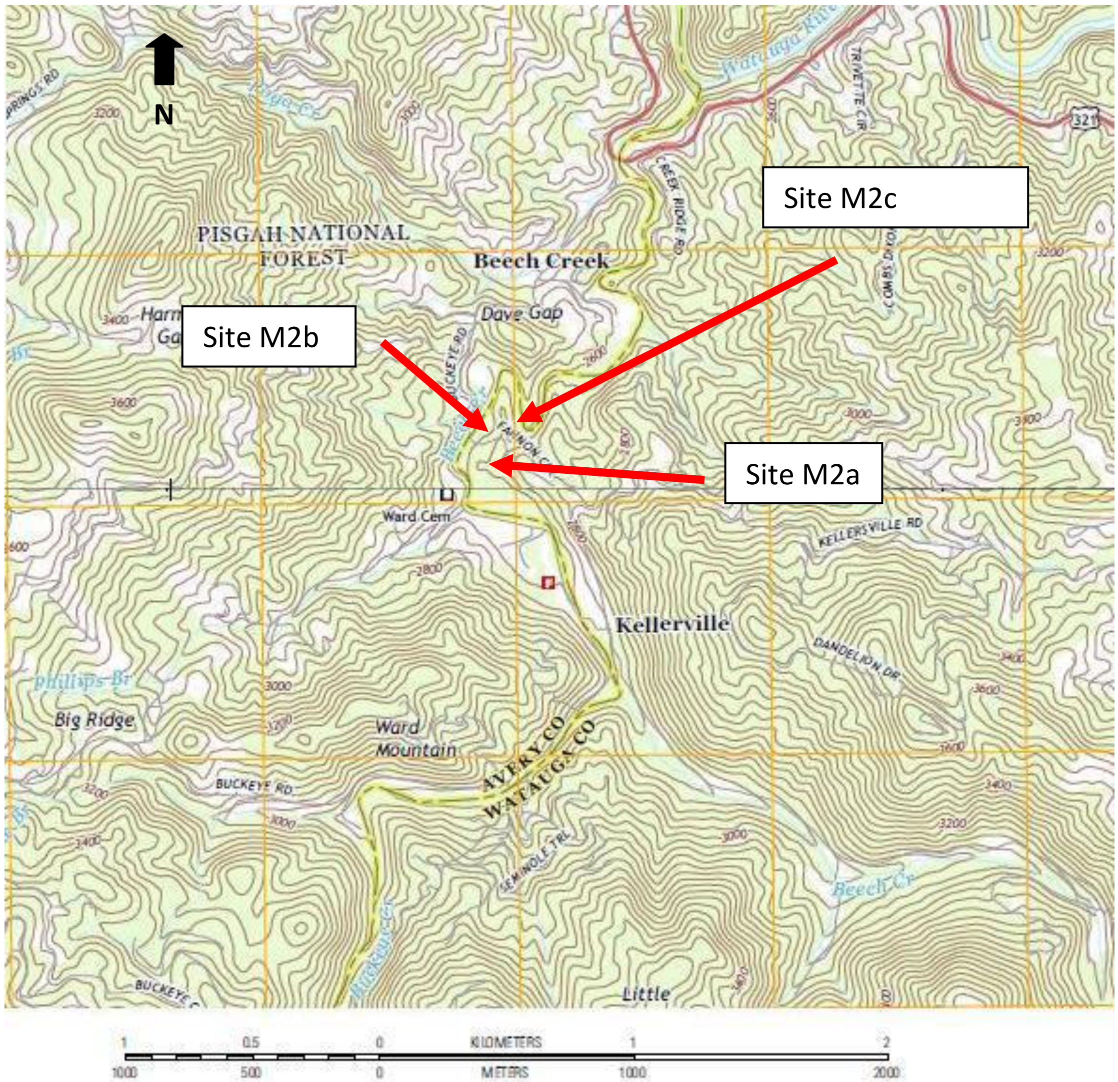

Figure A4. M2a, b, and c Sites, Beech Creek. (USGS Topo)

Site M2a

This site is notable for its anthropogenic past, which is well known to the author. In 1963 it was excavated for gravel and sand, leaving a barren desert-like terrain consisting of loose rock and sand atop the underlying bedrock, with Beech

Creek running adjacent, but separated from, by an earthen dike approximately 5 m tall. It remained in this state until 1974, when the northern (downstream) section was covered in topsoil for growing crops. This comprised of an “L” shaped area approximately 30 meters wide and 100 m long on both the north and east sides of the area. In the late 1970s the bottom began to develop vegetation along several spring seeps, and by 1988 the bottom was completely revegetated with a variety of low grasses and forbs. Spring seeps developed several waterlogged areas, and in 1992 beaver began to use the southwestern corner, first damming a drainage channel, then expanding upstream in the drainage channel along the southwest side of the field. By 1998 dams extended along the topsoil section in the northern corner, creating several 2,000-5,000 m^2 ponds. All large dams were breached and partially removed during flooding caused by Hurricane Ivan in 2004 which also breached the earthen dike protecting the land; however, visible rebuilding began in 2006 and has continued to present, as the current landowner places an economic value on the pond and protects the beaver population. Currently, the primary dam is 90 m in length, with a maximum height of 1.5 m and maximum width of 3 m. There are numerous submerged dams from former construction, with the location of 7 identified through long-term observation as the dam was constructed; likely there are several others whose construction was overlooked before being submerged. Two other dams are upstream from the primary dam, one 12 m long and the other 5 m; both are approximately 1 m tall and 1.5 m wide. The two smaller, upper dams are comprised of a wattle and daub construction, with a large amount of herbaceous material included in the construction. The lower, primary, dam is also wattle and daub, but contains a much greater proportion of earthen material, over 50% by volume, than the others. This is likely due to the ready availability of the topsoil in the area (moved in for farming in 1974.) It also contains a considerable amount of herbaceous material. This site complex provides a reference to compare against other sites, as the topography underwater is known and the sequence of building observed over a 23 year period.

The first item of note is the presence of an abandoned bank lodge in the area of original dam construction on the northern corner. Beaver activity in this area resulted in a large (2mx2mx1m) pile of used food branches, ranging in diameter from 3-18cm; this persisted even through Hurricane Ivan floods, which dislocated the beaver for 2 years. This discard area came back into use in 2011 as the larger dam was completely, and now covers an area approximately 5mx8m, and 1.75 m in height. It continues to grow as discards are added, and probing in/near it indicated an elevation of the pond bottom of approximately 20cm due to accumulated sediment in the tangle. (Figure A5) As can be seen in the upper left of the figure, another discard pile is beginning to form, and will likely become enmeshed with the first over time, forming a substantial accumulation of immobilized LWD. The long-term persistence of this woody debris aggregation, even through flooding that removed much of the dam, indicates that these structures may become long-lasting features of the microterrain of beaver ponds and later beaver meadows.

Figure A5. Food Discard Woody Material, approximately 1.5 m Deep at this Point. (Author)

The second item of note in this pond is the development of a large lodge (figure A6.) This lodge is built against the edge of the former topsoil relocation area, and limited investigation (as it is an active lodge) indicated a primarily earthen construction with <10cm woody material and herbaceous materials forming a fibrous structure. The lodge is 3.5m wide, 6m long, and approximately 1.8 m tall, forming a substantial structure with potential for long term retention of the materials contained within its construction. Probing depth around the lodge indicated two channels leading into it, both approximately .5m deeper than the surrounding water, which may also continue to influence the microterrain of the area after abandonment.

Figure A6. Beaver Lodge. Approximately 1 m above Water Level with .8m Submerged. (Author)

There are 5 other channels in evidence around the pond; these, however, are excavated from the edge of the pond into otherwise dry land to reach new food sources. These channels range from 2 to 6 m in length, with a rough cross section of .6 meters wide and .4m deep. Probing near these indicated that at least three were continuations of earlier channels from lower water levels, and that the earlier channels still existed as underwater trenches; one extending approximately 6 meters into the pond with a terminus in just over one meter of water.

Underwater excavation was noted along the entire upstream length of the primary dam. Whereas the rest of the pond has a soft, sediment/organic layer, the upstream base of the dam exhibits a trench area varying from .5 to 1.5m wide of hard rock, the original base of the gravel/sand mining operation. This material is apparently used to construct and maintain the primary dam, along with the relocated topsoil material from the earlier farming operation. The greatest depth of the pond was noted just upstream of the dam foot, at 1.45m.

The last item of interest to this study is the development of multiple channels in the upper area of the primary (downstream) pond, somewhat resembling a delta area, and in the smaller upper ponds. These demonstrate an anabranching form, with the potential to persist after the abandonment of the complex due to the erosion resistant, heavily vegetated bank areas.

Site M2b

This site is a failed dam in Beech Creek, 350 m below M2a. It was constructed in Spring 2008, and failed after 3 months during a high flow event. The construction was entirely different from M2a, being composed almost entirely of woody materials with rocks and small amounts of earthen and herbaceous materials. At this location Beech is tightly confined with less than two meters of “valley bottom” on either side before reaching steep (>5.7) banks. High flow events are confined until reaching the top of the bank (3+m), and as a result exhibit a strong scouring action. After the washout, no visible trace of the dam remained in the stream.

Site M2c.

Similar to M2b, 400 m further downstream. This dam was begun in Spring 1997 and washed out in Spring 1998, lasting just over one year. While predating this study, it was examined at the time and found to be what was later deemed Sticks and Stones construction, with numerous rocks from baseball to football size. The rock remains persisted until high flows in 1999.

Site M3, Camp Creek, Burke County, NC

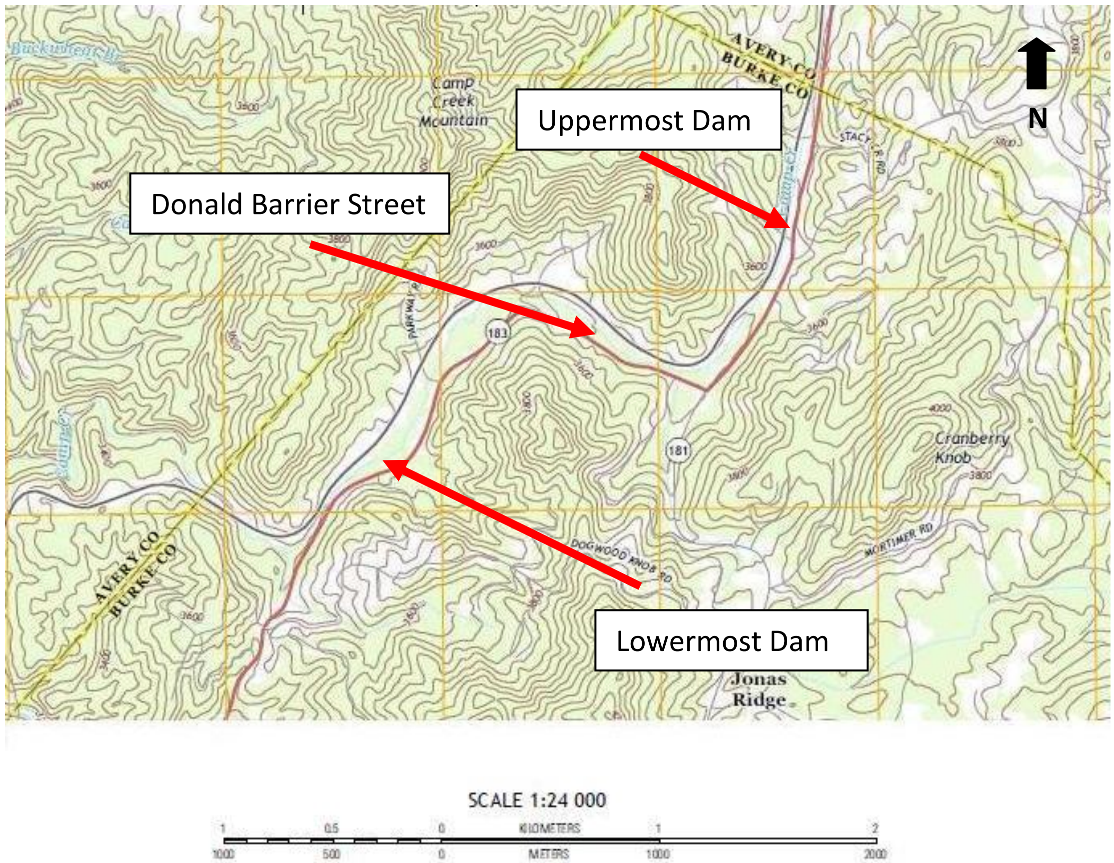

Figure A7. M3, Camp Creek, NC. (USGS)

The Camp Creek site is a large complex on a first order stream, consisting of 9 large dams, 15 smaller dams, and numerous wing/check dams, with a total impact of 3,100 m of valley. Grade of the affected section is .03, with a maximum valley floor width of 108 m. This complex is very near the headwater of Camp Creek, with the uppermost pond approximately 650 m from the stream origin. There are 5 small first order streams entering into the site along with several road culverts representing ephemeral flows. According to local landowners, the complex began in approximately 1999, with continuous activity since that time.

Upper Reach

The uppermost area of activity in the Camp Creek Complex, damming has created a large (2 hectare+) meadow of anabranched streams (figure A8, A9), ephemeral channels (figure A10), and small check dams (figure A11), with a large quantity of both standing and fallen woody material.

Figure A8. Upper Camp Creek Complex. (Author)

Figure A9. Upper Camp Creek Complex, Branching Channel, likely formed from an earlier Beaver Canal. (Author)

Figure A10. Upper Camp Creek Complex, Ephemeral Channel. (Author)

Figure A11. Upper Camp Creek Complex, Check Dam. (Author)

In this section there are numerous conglomerations of woody debris, some food discards or food storage, some aggregated due to stream flow, and some randomly throughout the area, apparently left as a result of deposition during higher pond levels. These features are found throughout the entire 3,100 m reach of activity. During the initial site survey, 3 primary channel dams (>3m length), 12 check dams, 9 flowing anabranches, 11 ephemeral channels, and 9 LWD accumulations were identified.

In the 1994 aerial photograph, no evidence of beaver activity is apparent (figure A12); this remains the case until 2013 (Figure A13), when beaver activity is obvious with widening channels due to dams, and the appearance or multiple channels in the lower left section of the figure.

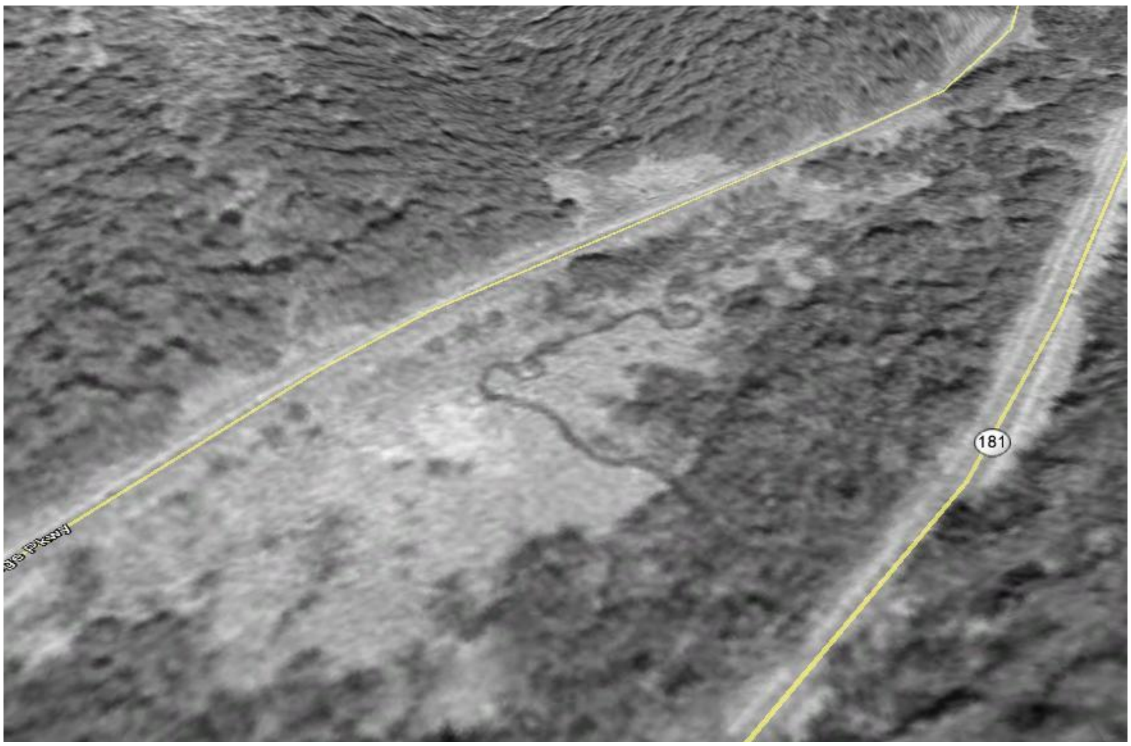

Figure A12. 1994 Aerial Photograph of Site M3 Upper Reach. (Google Earth)

Figure A13. 2013 Aerial Photograph of Site M3 Upper Reach. (Google Earth)

Of note at the lower end of this reach is a dam constructed of wattle and daub style, but the woody material is almost entirely rhododendron (*Rhododendron* sp.) (Figure A14.) This dam was constructed in the summer of 2013 and sporadically maintained until all beaver activity ceased in 2014, flooding a small <500m^2 area. No rhododendron bark was eaten, and only small amounts of hardwood food trees were reached by this effort. No lodge was found in this area.

Figure A14. Rhododendron Dam. (Author)

Middle Reach

In the middle section of the reach one dam near a bridge has been breached several times due to threats to the bridge. According to nearby landowners, the dam (just downstream of Donald Barrier Street) was breached sometime in the 2008-2009 time frame, and during the study period, the dam (Figures A15, A16) was breached in 2013 (though rebuilt within 5 months), and breached again in summer 2014 and has not been rebuilt as of this writing. The dam below Parkway Road was breached in 2013, and has not been rebuilt.

Beaver activity at the site began to decline in 2014, and by Spring of 2015 has ceased, apparently due to removal of the beaver population.

Figure A15. Camp Creek, Dam below Donald Barrier Street before Breaching. May, 2013, during a high flow event. Note large rootwad in center. (Author)

Figure A16. Camp Creek, taken from Bridge in Figure A15, after Breaching. Note large Rootwad, the tip of which is visible in Figure A15, and which has been present in this location for 4 years. (Author)

The area just above Donald Barrier Road consisted of a large shallow pond with a low dam, approximately 1 meter tall, 1.75 m wide and 100 m long upon the first site visit in 2012. During a high flow event in 2013 the dam was overtopped, which provided clear visible evidence of its extent (figure A17.)

Figure A17. Dam above Donald Barrier Street during High Flow, May, 2013, demonstrating Extent of Dam. (Author)

This dam was maintained until Spring 2014, when beaver activity in the area ceased. Over the next year, the pond drained and the area transitioned to a well-vegetated bog area (figure A18), with Hazel Alder (*Alnus serrulata*) being the first (and as of this writing, only) woody plant species to colonize the area. This meadow now contains 5 LWD piles, 3 check dam remnants, 3 running stream channels and 5 ephemeral channels, plus the original dam is largely intact and now well-vegetated.

Figure A18. Camp Creek Site, August 2015. Note dead Hemlock (center) as reference to Figure A17. (Author)

Figure A19 illustrates this area in a 1994 aerial view, before significant beaver activity in the area. The road in the center is Donald Barrier Street; note that the majority of the area is wooded. Figures A17 and A18 were taken upstream of the bridge (right side in figures.)

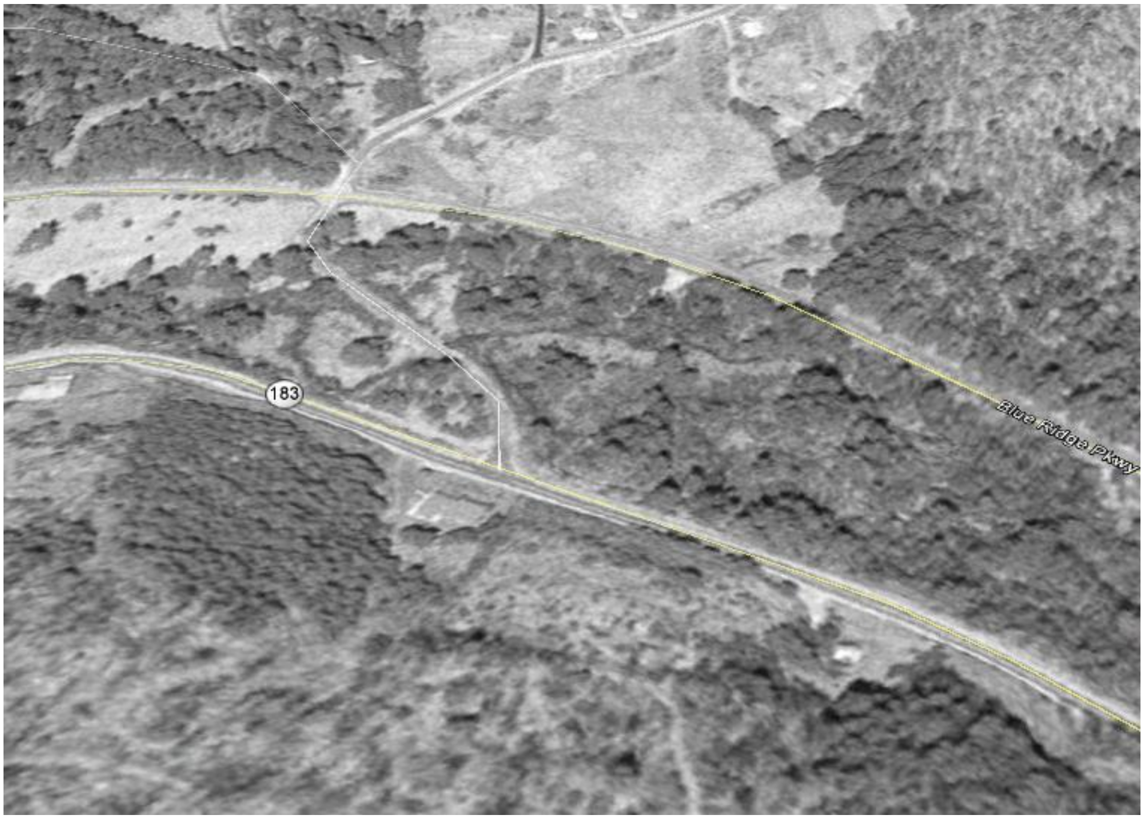

Figure A19. 1994 Aerial Photograph of Donald Barrier Street Area. (Google Earth)

By 2005, beaver activity has created a wide pond across the area, resulting in some loss of trees (Figure A20), and by 2013 the pond is quite extensive with continued tree loss due to beaver predation and inundation (Figure A21.)

Figure A20. 2005 Aerial Photograph, Donald Barrier Street Area. (Google Earth)

Figure A21. 2013 Aerial Photograph of Donald Barrier Road Area. (Google Earth)

Changes in the area immediately downstream (left side of bridge in figures) of the bridge are evident as well, with tree loss and inundation following the same pattern as above the road.

Lower Reach

The lower reach of impacted area was abandoned in 2010, and no activity was noted after that time. As figure A22 shows, by 2005 the area had been subject to intensive beaver activity for some time, with no large trees and minimal shrubs visible. Numerous channels are also visible in this view. By 2010, inundation has increased and channels have become more clearly defined (Figure A23.)

Figure A22. 2005 Aerial Photograph of Site M3 Lower Reach. (Google Earth)

Figure A23. 2009 Aerial Photograph of Site M3 Lower Reach. (Google Earth)

By 2011 the dams in this reach had been abandoned and the ponds drained, leaving a network of anabranched channels through the former pond areas. Herbaceous vegetation has colonized the area, though woody growth is just beginning. (Figure A24.) Woody growth (primarily Hazel Alder (*Alnus serrulata*) has moved in extensively by 2013, and the former pond area has an extensive series of channels through it, visible in Figure A25.

Figure A24. 2011 Aerial Photograph of Site M3 Lower Reach. (Google Earth)

Figure A25. 2013 Aerial Photograph of Site M3 Lower Reach. (Google Earth)

As of this writing, the site is well-covered with both herbaceous material and Hazel Alder (*Alnus serrulata*), though no recruitment of larger hardwood or softwood species has been noted. Several anabranches have lost water sources and remain as ephemeral channels, several have remained stable, and several have consolidated into larger channels. The ephemeral channels have become well-covered in grasses and forbs, and appear to be stable, erosion-resistant elements of the landscape at this time.

M4, Conely Branch, McDowell County, NC

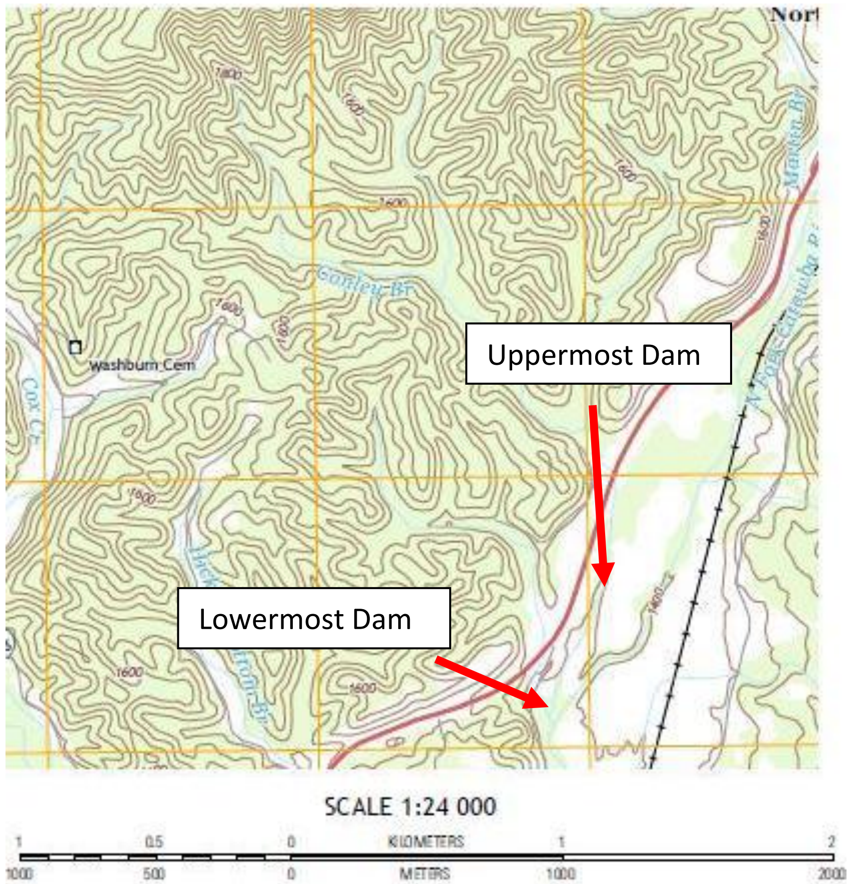

Figure A26. Site M4, Conely Branch. (USGS Topo)

M4 consists of 4 primary dams and 3 wing dams, impacting 275 m of Conely Branch in McDowell County, NC, adjacent to NC 221. Beaver activity began on this site in approximately 1999, and the site remains active. The upper limit of this complex is a culvert under NC 221 (figure A27), thus preventing any direct upstream movement of the dam complex..

Figure A27. Culvert “Headwater” for Site M4. (Author)

All four primary dams in this section were composed of beaverlith, though the lowest one exhibited considerably more woody material than most of the other dams at the site. Two possibilities exist for this: first, this dam is in a more heavily wooded section of the reach and the material was readily available, or second, that this lowermost dam was trapping woody materials generated by both the surrounding forest and upstream beaver activities. Five sample pits, including one on the submerged upstream face of the dam confirmed a construction of primarily soil, though the downstream face was the most heavily wooded of any beaverlith dam in the study. I believe that due to the slightly more incised nature of the stream in this area, this dam was likely begun as a wattle and daub dam until sufficient area was flooded to access inundated soils, at which time the major component of the dam shifted to soil (Figure A28.)

Figure A28. Lower Dam at Site M4, showing Heavily Wooded Downstream Face, though underlying Dam is primarily Beaverlith. (Author.)

Another attribute of this site was a breached beaverlith dam upstream of the last downstream dam. The reason for breaching is unknown, but the remaining wings have persisted in unchanged form since 2011, giving some idea of the durability and erosion resistance of this form of construction. (Figure A29.)

Figure A29. Breached Beaverlith Dam, width 1.9 m at Waterline. Note gentle Slope on the Upstream (left in photo) Face, with much shaper slope on Downstream Face. This Profile is a result of Woody Material on the Lower Face being removed during High Flows, while the erosion-resistant Beaverlithic Material, including Woody Debris incorporated into the Beaverlith, remains. (Author)

Figure A30. The 2013 Aerial Photgraph shows the extent of the Site, paralleling NC 221 on the west (left side.) (Google Earth)

Site M5, South Fork Lewis Prong. Wilkes County, NC

Failed Wattle and Daub dam. Dam lasted approximately 3 months during the summer of 2011, and was washed out in the Fall. Remains consisted of a cobble shelf across the stream, 6.5m long, .5m wide, and ~10 cm deep. This shelf was not consistant across the width, but followed the outline of the failed dam and visually persisted for 4 months.

Site M6, Catawba River, McDowell County, NC

Failed dam, likely Stick and Stone. Site was discovered based on information indicating an active dam was present at that location: however, ground investigation revealed evidence of beaver activity and a remaining shelf of cobble extending across the streambed, 7m in length, 1m wide, and ~15 cm deep. This cobble "path" across the river was later modified through anthropogenic activity, so its natural duration time is unknown. Of note at this location is the formation of a large beaver dam on a tributary 25m from the failed site, which has now covered an area approximately $600m^2$; this later dam is not included in this study.

Site M7, Yadkin River, Caldwell County, NC

Failed dam, likely Wattle and Daub or Stick and Stone construction. Site visually noted during another study and later confirmed to be the result of beaver activity. Cobble shelf across streambed approx 6m long, 1.5-2m wide, depth unknown. Remains were observable over at least a two-year period, though it is unknown how long the remains had been in place before discovery.

Site P1, Unnamed Tributary of the PeeDee River, Stanley County, NC

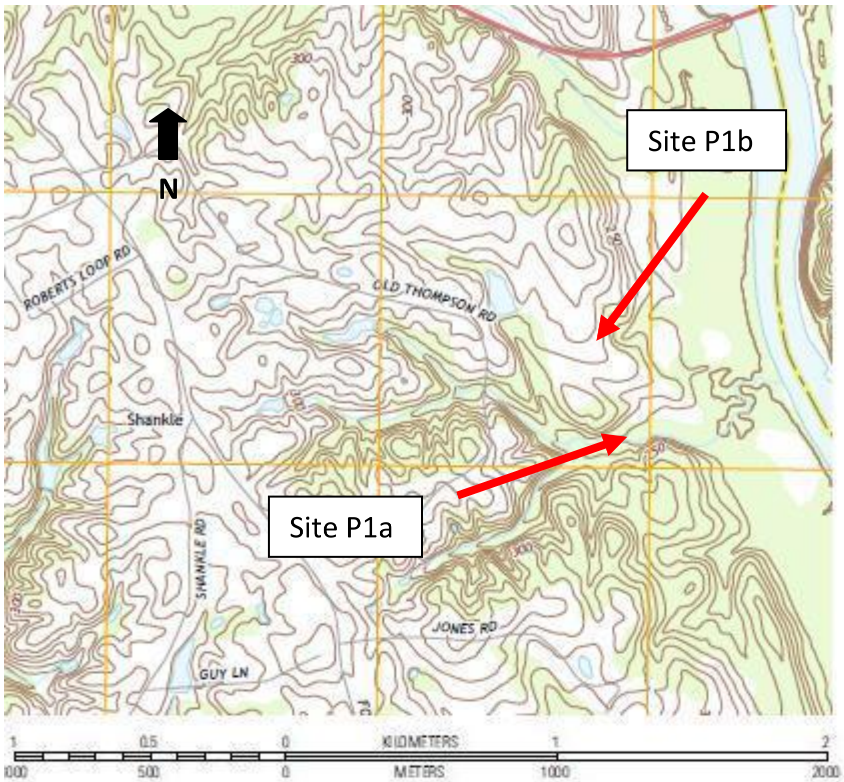

Figure A31. Site P1a and P1b. (USGS Topo)

This site consisted of two separate dam complexes, discussed separately below.

Site P1a

This site was located on the southern fork of an unnamed tributary stream to the Pee Dee River below the Lake Tillery Dam. The landowner provided a background for the site, which included a history of beaver activity and removal back to the mid-1990s. After he and his wife acquired the land in the mid-2000s, beaver removal ceased, and efforts were made to limit damage caused by inundation. To this effect, several leveling devices were installed (all failed), and a section of field was ceded to beaver flooding. Primary amelioration efforts at this time consist of staged dam breaches to prevent flooding of a farm road through the property. This breaching routine is ongoing, and repeated on a roughly two week cycle. It was at this location that I was allowed to excavate transects through several beaverlith dams and conduct other experiments on dam erosion and construction (Figure A32.)

The dam complex begins with 5 wattle and daub dams in a 2-3m deep incised stream (Figure A33), forming a series of lock-like pools. Several short canals were found in this area, as well as several beaver slides.

Figure A32. Excavating a Transect across a Beaverlith Dam. (Author)

Figure A33. Wattle and Daub Dam in Incised Stream. (Author)

This series of dams ended near the farm field previously mentioned, and the large pond formed by one of the primary dams on the stream, which also marked the transition to a beaverlith construction (Figure A34.) One important feature of this and the other two beaverlith dams on this reach was the vegetation that had become established on the dam top and downstream face, adding a stabilizing cover to the dam. Also noticeable in figure A34 is the accumulation of earthen material on many of the woody stems, indicating that the beaver are continuing to add to the height of the dam.

Figure A34. Portion of First Main Beaverlith Dam; note Vegetation growing on Dam. (Author)

Outlets in this first dam, in the former field area, created 7 different channels leading to the next dam, 6 anabraches and one main channel. All were taken in by the next dam, which, although having several outlets, formed no visible anabranching due to the pond from the final dam backing up to it. However, wading and probing indicated the presence of at least three submerged channels emanating from the downstream dam face, likely artifacts predating the construction of the last dam. The final dam was only 3m from the road culvert, and thus the downstream face of this dam was regularly cleared by the landowner and was a secondary breaching spot to lower water threatening the road. Due to this anthropogenic activity, the lower dam had only one outlet leading directly into the culvert.

Throughout this system numerous canals were noted extending into unflooded areas, and wading the shoreline revealed the presence of several more submerged by the rising pond level (figure A35.)

Figure A35. Beaver Canal. (Author)

Site P1b

This site, on the northern fork of the tributary, consisted of only two dams, one wattle and daub and one beaverlith, though the wattle and daub dam contained far more soil material than other dams of that type in this study. The upper dam was located in a washed-out section of former roadbed built across the tributary, likely the location of a culvert many years prior. This created an ideal situation for damming, as little effort was required to flood a considerable area of land, just under 2 hectares (Figure A36.)

Figure A36. Upper Pond of P1b. Filled with Stumps of Beaver-cut Trees. (Author)

Other than the size of the pond and number of beaver-cut stumps in the water, this was an unremarkable dam, as no anabranches were formed in the focused outlet. However, if activity continues without anthropogenic interference, the pond will likely top the old roadbed, which will likely result in numerous anabranches. These, however, are the result of former anthropogenic activity and not solely a result of beaver action.

The downstream dam in this complex was remarkable for its size and durability. This dam was constructed in an incised stream channel which measured (on the downstream side of the dam) 2.5m wide at the bottom, 4m high, and 7m wide at the top. (Figures A37, A38.)

Figure A37. Top of large Beaverlith Dam. (Author)

Figure A38. Downstream Face of large Beaverlith Dam. (Author)

This dam was constructed sometime around 2000, and has been covered by up to 2m of water on one occasion as a result of flooding during a high flow event combined with a release from Lake TIllery. Due to the incised nature of this stream channel, no anabranching was present.

Site P2, Upper Richardson-Taylor preserve; unnamed tributary of Long Branch, Guilford County, NC

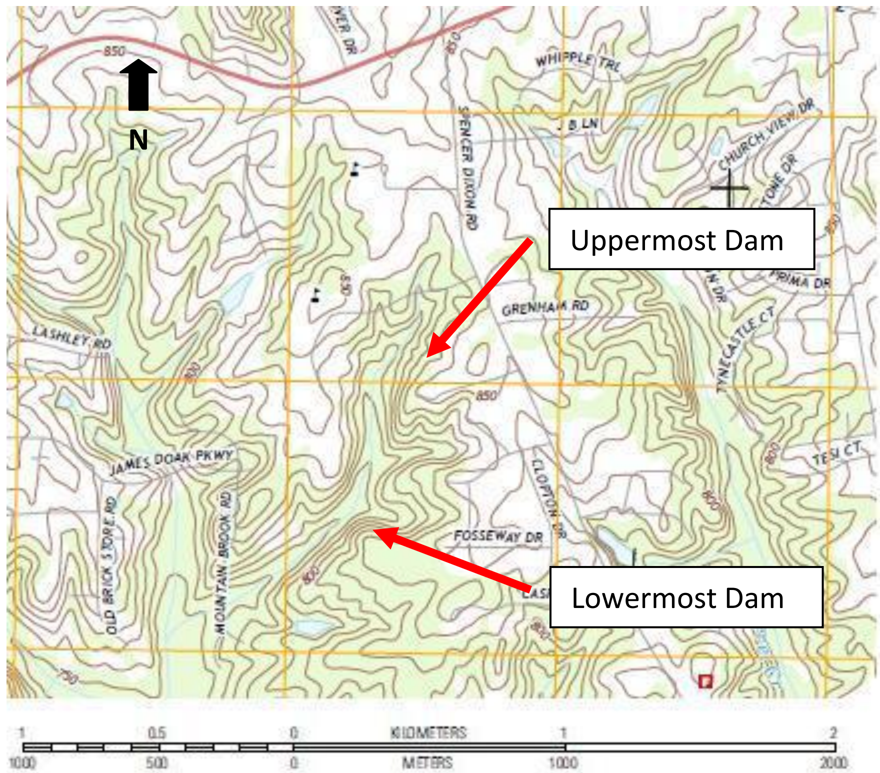

Figure A39. Site P2 Upper Richardson-Taylor Preserve, Guildford County, NC. (USGS Topo)

This complex consists of 5 main dams and 6 check dams, and originated between 2003-2004. All dams, including check dams, were of beaverlith construction, and the site was notable for the large amounts of woody debris in the form of cut and fallen trees in the ponds, incorporated into dams, and in the downstream areas below dams. Of note in this site is the failure of lower dams to back up water to the upper dams, a feature seen in most other multi-dam sequences. This, coupled with long dams and multiple outlets, allowed for anabranching channel systems to form below each dam in the waterlogged but uncovered area between dam and pond. As the aerial photo from 2008 (figure A40) shows, the dams were originally spaced at some distance on the streams; by 2013 the trees in the inter-dam zone have died or been cut, leaving an exposed network of channels between dams (figure A41.)

Figure A40. 2006 Aerial Photograph showing Development of Dam Sequence and Spacing. (Google Earth)

Figure A41. 2013 Aerial Photograph showing loss of Trees in Inter-Dam Zones, and Anabranching Channel System Form. (Google Earth)

The beaverlith dams have developed a herbaceous covering, stabilizing the dams surface, though in several places continued to cover this growing material with soils, forming a matted system of soil, dead vegetative material, deep root systems, and live plants growing through the new dam materials. This was found to be as much as 30cm deep in several locations, indicating that the dam surface, after a certain age, develops an extremely erosion resistant covering over time.

Site P3, Long Branch, Lower Richardson-Taylor Preserve, Guilford County, NC

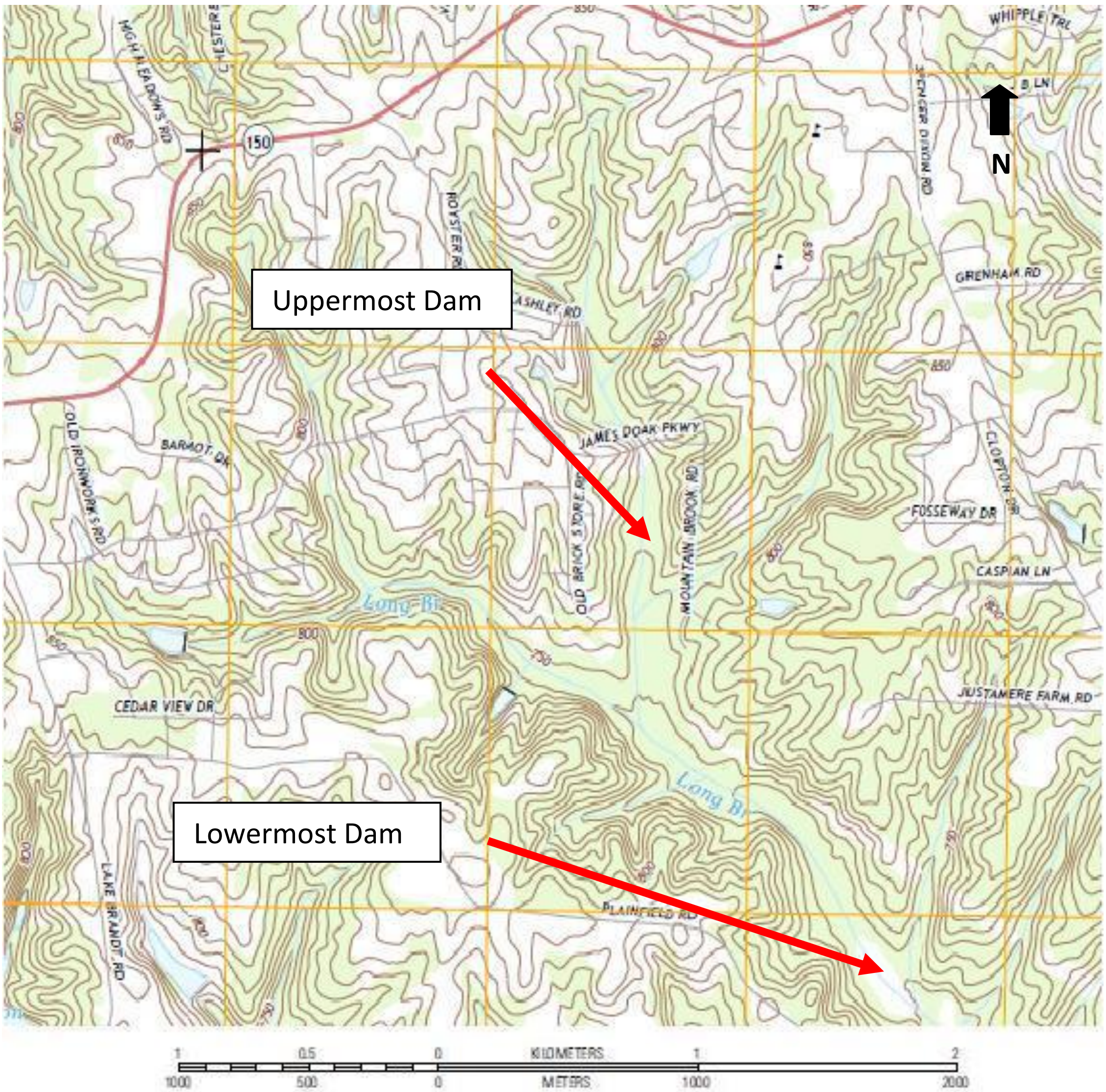

Figure A42. Site P3, Long Branch, Lower Richardson-Taylor Preserve, Guilford County, NC. (USGS Topo)

This site is 1.5km downstream of site P2 on a second-order stream, and is on the south end of the Richardson-Taylor Preserve. The complex ends at Lake Townsend, and consists of 4 primary dams and 11 check dams. Of note is that many check dams have been incorporated into primary dams as water levels have risen, leaving the primary dams traveling in a meandering path between shorelines, and increasing the dam length beyond a simple straight-line measure between shores. This site is also rich in large woody debris, both as a direct result of beaver cutting, and as a result of trees killed by inundation and falling into the water, and a great many trees remain standing deadwood, ready to contribute LWD for many years. Figures A43 and A44 provide an example of the rich assemblage of woody material collected in this complex of dams.

Figure A43. A Variety of Woody Debris at Site P3. (Author)

Figure A44. Another View of the Woody Debris at Site P3. (Author)

Lodges consisted of 5 visible beaverlith lodges, though this site was difficult to thoroughly inspect due to the large size and location within a preserve.

Anabranching was very clear in aerial photos of this site. Spacing between dams provided extensive saturated soils, and long (100m+) dams provided numerous outlets for water. The upper area (Figure A45) contained three long (200m+), separate channels through the potential meadow area, while one of the lower areas contained at least ten separate channels (Figure A46). Nearly all channels in this complex carried water, as opposed to site M3 where several channels remained only as ephemeral channels. However, M3 was recently abandoned, whereas P3 is currently active; ephemeral channels may develop at this site as well once abandoned.

Figure A45. Upper Area of Site P3, showing multiple channels. (Google Earth)

Figure A46. Lower Area of Site P3, showing Complex Anabranching Channel System. (Google Earth)

This site also had remains of an earlier, failed, dam just upstream of the last active dam. Waterlines on trees remained, indicated a depth of approximately 1m above the forest floor, and built in a slightly incised (75cm) stream channel. The pond had covered approximately 1,200m^2 area, and several woody food discard piles were present across the forest floor, along with several larger (3m+) tree trunks and dam remains. The reason for abandonment is unknown, but may have been due to dam loss in the early building stage due to a high flow event. The remaining standing trees had survived, indicating a short period of inundation, but the area was conspicuously devoid of small (<5cm diameter) trees, as shown in figure A47. The surrounding forest, including the area just upstream of this location, have considerable small tree and shrub growth, indicating that those plants were lost when the beaver initially colonized this area and have not regrown.

Figure A47. Previously Flooded Area in Upper Section; note Lack of small Trees and Shrubs. (Author)

Site P4, Big Alamance Creek, Company Mill Preserve, Guilford County, NC

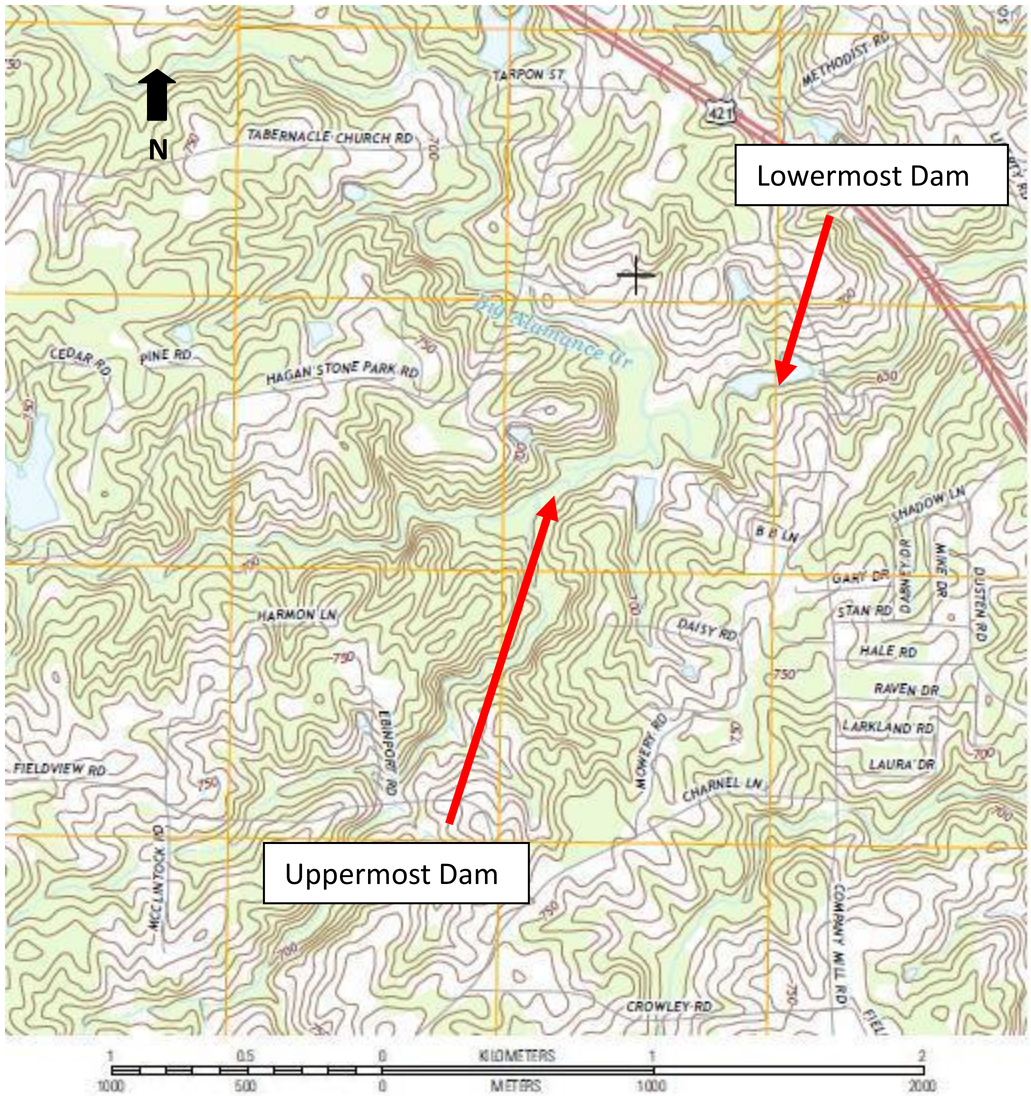

Figure A48. Site P4 Big Alamance Creek, Company Mill Preserve, Guilford County, NC. (USGS Topo)

This site involved a complex of 5 main dams and 8 check dams, impacting a 1,100m reach of Big Alamance creek upstream of a disused mill dam. Woody debris accumulation was similar to site P3, though LWD tended to be both sparser and larger (figure A49.) Fewer patches of small woody debris (<5 cm) were noted, but multiple channels, inundated areas, sediment accumulation, and terrain prevented a thorough examination of some areas of this site.

Figure A49. Woody Debris at Site P4. (Author)

Anabranching took two forms at this location; the first being smaller channels similar to P2 and P3 (figure A50), the second much larger (figure A51.) The smaller channels ranged from .5m to 2m, and were located primarily in waterlogged soils with limited terrestrial vegetation for stabilization. As this was an active site, no ephemeral channels were noted. The larger channels, ranging from 3m to 6m in width, were located in a more stabilized area, with non-inundated soils and substantial vegetation (including some woody shrubs and resprouting trunks) acting to stabilize areas between the channels.

Figure A50. Small Anabranching Channels Connected to Main Channel, Site P4. (Google Earth)

Figure A51. Large Anabranching Channels, Site P4. (Google Earth)

Several old dam sites were identified, indicating that this location had been used more than once by beaver, and a probably predate the current activity by many years. Aerial photos as early as 1999 (Figure A52) clearly show the large anabranched channels also shown in figure A51. These channels remain stationary from that point onwards, though clear signs of the current beaver activity only begin to show up on aerial photos in 2008 (figure A53.) Further investigation of these channels might determine a precise origin, but the evidence of old dam sites provide a strong case for beaver-related origins.

Figure A52. 1999 Aerial Photograph showing Anabranched Channels in Lower Center. (Google Earth)

Figure A53. 2008 Aerial Photograph, showing Beaver Activity in Upper Right Center. (Google Earth)

Site C1, Big Thompson Swamp, Greene County, NC

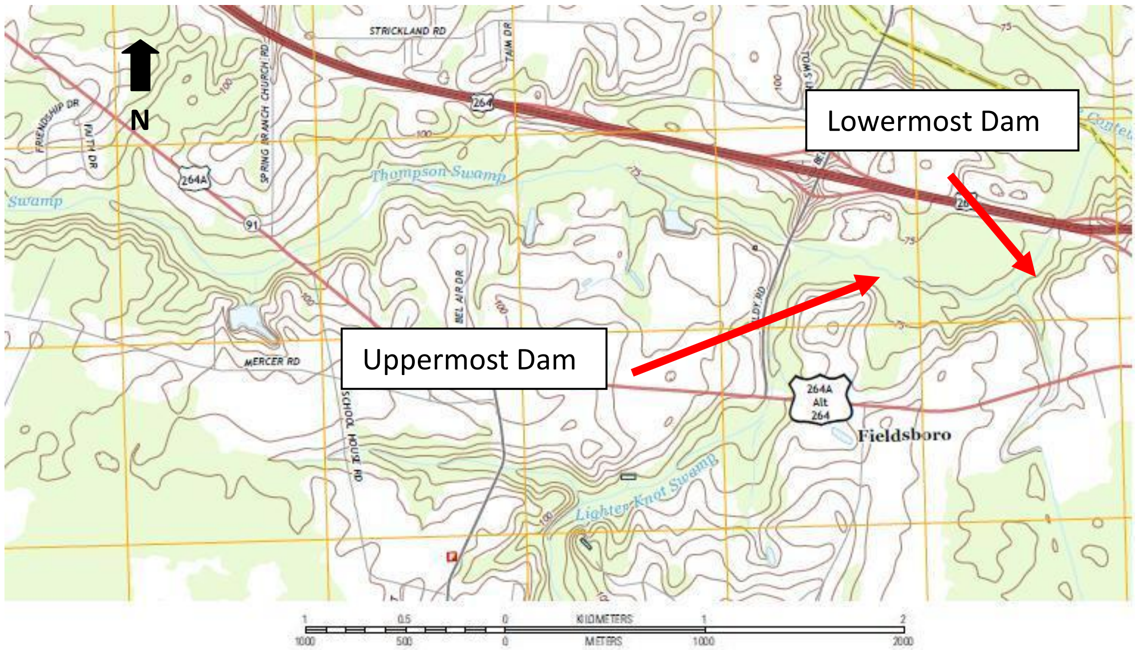

Figure A54. Site C1 Big Thompson Swamp, Greene County, NC. (USGS Topo)

This was the only coastal site included in the study for purposes of comparison to the other sites. This site has been used multiple times throughout the last 25 years, with continued episodes of colonization, beaver removal and dam breaching, and recolonization. The dam in use during this study was started in 2009 and breached in 2014, with a residence time of approximately 4 1/2 years. During this time, the main downstream dam reached a length of 90 meters and inundated an area of approximately 4 hectares. This was the only dam surveyed with a large economic loss, as it destroyed that portion of a pine plantation forest. This site, despite the low gradient, developed few anabranches;

the only observed multiple channel area was on the downstream dam face where three separate water outlets created a short (20m) section of branched streams before rejoining into one channel in the former streambed. As these were "forced" channels due to elevated water outlets across the dam face, they represent a sort of contrived anabranching situation, unlikely to persist after dam abandonment. However, it is possible that, given a lack of human involvement, the channels could persist long enough to erode distinct and long-lasting features in the downstream area, and may well have done so in a pre-European context. Regrowth in the former pond area was rapid, with grasses and forbs covering the entire area in less than 6 months.